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VTT TECHNOLOGY 122

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ISBN 978-951-38-8046-0 (Soft back ed.)
ISBN 978-951-38-8047-7 (URL: http://www.vtt.fi/publications/index.jsp)

VTT Technology 122

ISSN-L 2242-1211
ISSN 2242-1211 (Print)
ISSN 2242-122X (Online)

JULKAISIJA – UTGIVARE – PUBLISHER

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PL 1000 (Tekniikantie 4 A, Espoo)
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Kopijyvä Oy, Kuopio 2013

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Puun torrefiointi – pilot-kokeet ja käytön edellytykset.
Carl Wilén, Perttu Jukola, Timo Järvinen, Kai Sipilä, Fred Verhoeff & Jaap Kiel.
Espoo 2013. VTT Technology 122. 73 p.

Abstract

The research project "Torrefaction of woody biomasses as energy carriers for the European markets" was carried out within the Tekes BioRefine programme in 2010–2012 and was coordinated by VTT. The main objective of the project was to create a discussion platform and collate basic information for the Finnish industrial stakeholders involved in developing torrefaction technology or planning to include torrefied biomass in their fuel supply for energy production.

Given the availability of torrefaction pilot facilities in Europe, it was decided at an early phase of the national torrefaction research project not to build and operate separate pilot equipment, and thus save time and money. Experimental research was conducted in cooperation with ECN, The Netherlands. Finnish wood chips and crushed forest residue were tested at different torrefaction temperatures in the PATRIG torrefaction test rig with great success, and large quantities of torrefied wood chips and pellets were produced.

CFD simulation work was carried out at VTT to investigate the feasibility of torrefied fuels to replace part of the coal. From the combustion point of view it seems feasible to replace coal by torrefied wood biomass with shares up to 50% by weight.

Basic, small-scale experiments were carried out to compare torrefied wood pellets with conventional wood and straw pellets with regard to their handling and storage properties. The experiments showed that the torrefied pellets are clearly more hydrophobic than wood and straw pellets and do not disintegrate completely on exposure to water. A study on dust explosion and self-ignition characteristics indicated that the torrefied dust does not differ significantly from the normal biomass dust, but is clearly more reactive than coal dust.

Commercial development of torrefaction is currently in its early phase. The current general view is that most of the demonstration plants have technical problems, which have delayed their commercial operation. The market is expected to move forward but the available public information is very limited, especially concerning the technologies used and volumes produced. Woody feedstocks will be the main raw material source. The utilisation rate of forest industry residues and by-products is relatively high in the EU and wood supply in Central Europe remains more or less stable, hence the price of the raw material is at a fairly high level. The utilities' capability to pay for the product depends mainly on the national feed-in tariffs of green electricity. The energy price for the user is at least twice as high as that of coal.

Keywords Torrefaction, pellets, biomass, co-firing, pilot-plant, storage, safety issues, simulation

Puun torrefiointi – pilot-kokeet ja käytön edellytykset

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Tiivistelmä

Tutkimusprojekti ”Torrefaction – Uudet verkottuneet biojalostamot Euroopan pelto- ja metsäbiomassan energiakantajaksi” toteutettiin Tekesin BioRefine-ohjelmassa VTT:ssä vuosina 2010−2012. Tavoitteena oli luoda keskustelufoorumi ja koota yhteen perustietoa alan suomalaisille toimijoille, jotka ovat kiinnostuneita torrefiointiteknologian kehittämisestä tai suunnittelevat biohiilen ottamista polttoainevalikoimaansa.

Projektin suunnitteluvaiheessa päätettiin hyödyntää Euroopassa tutkimuslaitoksilla olevia pilot-kokoluokan koelaitteistoja oman laitteiston rakentamisen sijasta ajan voittamiseksi ja kustannusten säästämiseksi. Biohiilen tuotannon kokeellinen tutkimus tehtiin yhteistyössä ECN:n kanssa Hollannissa. Suomalaisilla puuhakkeilla tehtiin onnistuneet koeajot eri torrefiointilämpötiloissa PATRIG-koelaitteistolla ja tuotettiin merkittävät määrät hiillettyä puuhaketta ja siitä pellettejä jatkotutkimuksia varten.

VTT:ssä tehdyllä CFD-kattilasimuloinnilla selvitettiin hiilen korvaamista torrefioidulla puuhakkeella. Tuloksena todettiin, että polton kannalta kivihiiltä voidaan korvata pölypolttokattilassa biohiilellä ainakin 50 painoprosenttiin asti.

Torrefioiduilla pelleteillä tehtiin pienimuotoisia käsittely- ja varastointikokeita ja verrattiin torrefioitujen pellettien ominaisuuksia kaupallisten puu- ja olkipellettien vastaaviin ominaisuuksiin. Kokeet osoittivat, että biohiilipelletit ovat hydrofobisempia kuin puu- ja olkipelletit eivätkä hajoa täysin joutuessaan veden kanssa kosketukseen. Pölyräjähdys- ja itsesyttymistutkimuksissa todettiin, että biohiilen turvallisuustekniset ominaisuudet eivät merkittävästi eroa muiden biomassapölyjen ominaisuuksista, mutta biohiilipöly on selvästi reaktiivisempaa kuin hiilipöly.

Torrefiointiteknologian kaupallistaminen on edelleen Euroopassa kehitysvaiheessa. Usean demonstraatiolaitoksen tekniset ongelmat ovat viivästyttäneet laitosten kaupalliseen tuotantoon saattamista. Tuotannon odotetaan käynnistyvän, mutta käytettävästä teknologiasta ja tuotantomääristä on vain rajallista julkista tietoa. Tulevan käytön ensisijaiset raaka-aineet ovat puuperäiset polttoaineet. Koska metsäteollisuuden sivuvirtojen käyttöasteet EU:ssa ovat jo suhteellisen korkeat ja Keski-Euroopan puun tuotanto on vakiintunut, lisäraaka-aineen hinta on melko korkealla tasolla. Tuotteen maksukyvyn määräävät pääosin eri maissa maksettavan vihreän sähkön syöttötariffit. Torrefioitu puupelletti on käyttäjälle vähintään kaksi kertaa kalliimpi energiahinnaltaan kuin kivihiili.

Avainsanat Torrefaction, pellets, biomass, co-firing, pilot-plant, storage, safety issues, simulation

Preface

The research project “Torrefaction of woody and agro biomasses as energy carriers for the European markets” was carried out within the BioRefine programme of Tekes – the Finnish Funding Agency for Technology and Innovation during the years 2010–2012. The project was coordinated by VTT.

This publication summarises the results of experimental work carried out with Finnish wood fuels at the pilot and laboratory scale concerning the production of torrefied pellets, CFD simulation work on co-combustion with coal, determination of safety-related indices and small-scale storage tests. A brief assessment of the European market with a special emphasis on wood availability was carried out by Pöyry Management Consulting Ltd. Five of the companies co-funding the public national torrefaction project conducted pilot-scale milling and co-firing tests in Japan with torrefied pellets and coal. The results have reported to the funding parties in a confidential report.

The main objective of the project was to create a discussion platform for the Finnish industrial stakeholders involved in developing the torrefaction technology or planning to include the torrefied biomass in their fuel supply for energy production. Thus, the steering group comprised representatives of the organisations and companies funding the research project: Marjatta Aarniala/Tekes, Jorma Isotalo/ Pohjolan Voima Oy, Jukka Heiskanen/Fortum Power and Heat Oy, Matti Rautanen/ Metso Oy, Markku Karlsson and Heikki Ilvespää/UPM-Kymmene Oy, Jukka Rouhiainen/Helsingin Energia, Jaakko Soikkeli/Vapo Oy, Risto Joroinen/Metsä-Botnia Oy (later Metsä Fibre Oy), Kai Sipilä and Carl Wilén/VTT. Jorma Isotalo acted as chair of the steering group and Carl Wilén as secretary of the Torrefaction project in his role as project manager at VTT.

Major contributions to the project were made by Perttu Jukola/VTT (CFD simulation), Timo Järvinen/VTT (storage tests), Sampo Ratinen/VTT (fuel preparation for pilot tests), Fred Verhoeff/ECN (pilot tests), Javier G. Torrent/Laboratorio Oficial J.M. Madariaga (dust explosion and ignition tests).

The authors would like to acknowledge all those who have participated and contributed to the project as well as the steering group for active and fruitful participation.

Espoo, June 2013

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1. Introduction

Physical and chemical properties of biomass can be modified by a torrefaction process closer to the properties of coal to replace large volumes of coal in existing power plants and in coal gasifiers for syngas and transportation fuel production. Torrefaction is a thermochemical treatment of biomass at 200 to 300 °C, a clearly lower temperature range than in the classical charring process for coke production. It is carried out under atmospheric pressure and in the absence of oxygen and could be called a mild pyrolysis process. The main objective is to use torrefied biomass as a fuel, especially as a pellet, with similar grinding properties and storability as coal, for co-firing in power plants. Many pilot- and demonstration-scale plants are in operation in Europe and North America. However, full commercial-scale operation is still hampered by numerous technical constraints.

There is a growing interest in Finland and internationally to substitute fossil coal in power and heat production, given the potential for significant environmental benefits in terms of net CO_2 emission reductions. Wood pellets are currently used to replace coal in pulverised coal (PC)-fired boilers. Replacement shares vary between 5 and 15%, due to physical and chemical properties of the wood fuels. The relatively low energy content and fibrous nature of the wood pellets limit the combustion and pre-treatment in co-firing in existing PC boilers. The torrefied and pelletised biocoal product shows a large resemblance to coal. The higher volumetric energy density as well as the brittle physical nature of the torrefied pellets allows higher co-firing percentages, roughly up to 50% by mass, without major investments in modified handling and milling systems.

The market potential of torrefied biomass pellets is expected to be huge, considering the substitution of coal in large-scale power and heat product. Replacing coal on the market is strongly dependent on national and local feed-in tariffs. Without this support it will not be profitable to use torrefied biomass products, which typically may be twice as expensive as coal. The 2020 energy and climate strategy will set national targets for renewable energy in Europe. For Finland, more than 38% of final energy will be produced from renewable sources. The last remaining percentages are the most expensive ones. Often off-shore wind and biomass co-firing in existing coal-fired power plants are price competitors. In Finland the 2020 targets will require a coal substitution of up to 7 TWh/a in seven existing coal-fired combined heat and power (CHP) boilers. The priority of national incentives has been given to CHP power plants with high overall efficiency and maximised CO_2 reduction compared to condensed mode power production. In 2010 the coal consumption was 14 TWh in these boilers. In Europe, there are more than 100 pulverised coal-fired power plants in operation. Theoretically, a 1000 MWe condensed mode coal power plant will need an annual volume of 1.8 TWh, equal to 360,000 t/a, of wood pellets for 10% energy replacement. On top of torrefied or traditional wood pellet utilisation, there are alternative solutions to co-fire biomass in coal boilers. Co-gasification plants are operational in Finland and the Netherlands.

A potential market growth for transportation biofuels production is foreseen in the coming years. European 2020 targets call for a 10% share of renewable energy in transport, second generation biofuels being the fastest growing area. Torrefied biomass pellets can be fired up to 100% ratios in existing coal gasifiers for syngas and biomass to liquid (BTL) fuels, and synthetic natural gas (SNG) and alcohol production in Europe. The first demonstration plants are under construction in Europe. The EU directive proposal on indirect land use change will be a catalyst for this market by setting national limits on the use of raw materials, like cereals from food production. The maximum level will be 5% of produced biofuels. Optimised fluid bed gasification technologies developed in Finland by several companies and VTT can use various lignocellulosic biomasses without any pretreatment or additional costs.

This publication presents and discusses technical aspects of torrefied wood pellet production, handling and co-firing in existing coal boilers. The market assessment presents major trends in the European pellet trade, and elaborates on the availability of sustainable raw materials for torrefaction. Low ash content is often a prerequisite for high availability of the boiler, and therefore white wood is the typical biomass source. This may lead to a potential competition position with forest industry operations, currently covering more than 50% of European bioenergy consumption. In general, the sawmill industry is the largest wood processor in the EU with a 45% share of the total industrial wood intake. The pulp industry represents around 35% and the panel industry around 20% of the total industrial wood intake of 400 mm^3/a in the EU.

In a parallel torrefaction project, VTT, in collaboration with industrial partners, has developed new bioenergy carrier solutions integrated to forest industry operations in sawmills. Sawmills offer attractive business solutions for solid white or brown pellet production, as well as bio-liquids produced by fast pyrolysis technology from sawdust and forest residues. There are significant synergies for bioenergy carrier integration due to favourable procurement and logistics, energy and labour benefits. A typical European sawmill could produce 100–300 000 t/a energy products from regional raw materials and by-products. A new torrefaction process was developed and market analysis was performed, including a road map for demonstrations and market introduction in Northern Europe. Fuel pellet users are looking for upstream integration in the product chain. Torrefied wood production will in the future offer new business opportunities to various stakeholders. A report concerning these issues will be published in a VTT publication series later this year.

2. Torrefaction

2.1 The process

Torrefaction is a thermolysis process that subjects the feedstock to thermal treatment at a relatively low temperature of 200 to 300 °C in the absence of oxygen over a time span of 10–30 minutes. During the torrefaction process, the water contained in the biomass as well as superfluous volatiles are removed, and the biopolymers partly decompose, giving off various types of volatiles. The final product is the remaining solid, dry, blackened material which is referred to as “torrefied biomass” or “biocoal”. During the torrefaction process, biomass typically loses 20–30% of its mass, while only 10% of the energy content in the biomass is lost. This energy (i.e. the volatiles) can be used as a heating fuel for the torrefaction process. Since the torrefied product already loses a high amount of volatiles during the thermochemical conversion, there is less remaining for the following combustion step. However, the risk of biological degradation is not completely overcome, but fungal growth and microbial activity are reduced, as long as the torrefied material stays very dry. Torrefaction has been studied at laboratory and pilot scale with respect to different feedstocks and process parameters [1–6].

After the biomass has been torrefied it can be densified, usually into briquettes or pellets using conventional densification equipment, to further increase the density of the material. In addition, the biomass exchanges its hydrophilic properties to hydrophobicity, which allows an effortless storage that goes hand-in-hand with a greater resistance against biological degradation, self-ignition and physical decomposition in general. The combined torrefaction and pelletisation process, the TOP process, is shown in the block diagram in Figure 1 [6]. Drying of the biomass feedstock to a moisture content of below 20% is usually required before torrefaction. In case of biomass pelletisation without a torrefaction step, the preferred residual moisture content is below 10%. The size reduction occurs in the TOP process after torrefaction prior to pelletising. The electricity consumption of milling torrefied wood is lower than that of untreated biomass.

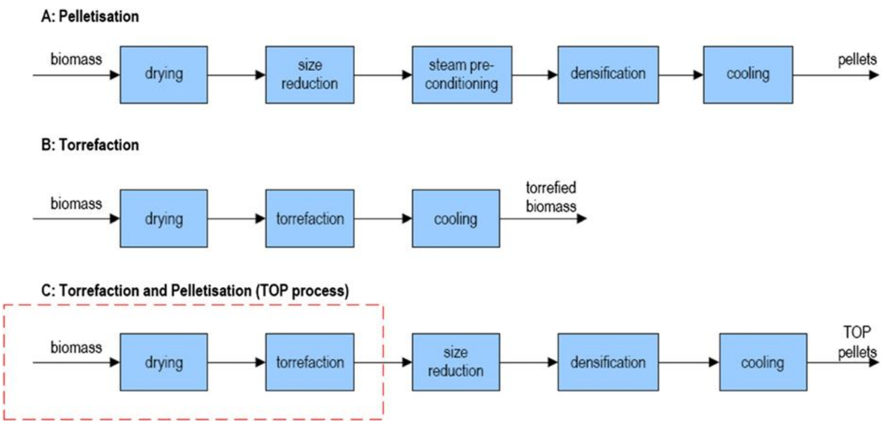


Figure 1. Pelletisation, torrefaction and TOP process schemes [6].

The primary goal in torrefaction is to refine raw biomass to an upgraded solid fuel, including better handling qualities and enhanced combustible properties similar to those of fossil coal, leading to decreased costs. The essential principle in this respect is to increase the energy density of the biomass (roughly 30%), requiring a growth of the ratio between energy and mass. Consequently, the calorific value of torrefied biomass increases as well. During the process, the structure of biomass changes, leading to new properties that make the handling of the final product much easier and also offers the possibility to utilise it in existing coal-fired boilers.

2.2 Co-firing and grindability

There are several options to introduce biomass co-firing in a coal-fired PC boiler plant, as described in Figure 2 [7]. Pathway 2, pre-mixing biomass (wood pellets) with coal and milling and firing the mixed fuel through the existing coal firing system, is done at a small number of power plants in Europe. The co-firing ratios are modest, generally less than 10% on a heat input basis [7]. Significantly higher ratios are expected when co-firing brittle torrefied biomass pellets due to their better grindability in the coal mills.

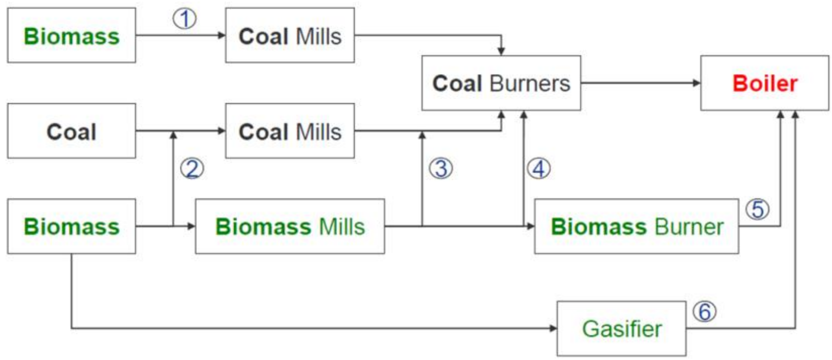


Figure 2. The principle of direct and indirect co-firing options [7].

The grindability of the biomass is enhanced by torrefaction due to the modification of its molecular structure, so that existing problems arising from untreated biomass in the milling component of a coal power plant are overcome. The grindability of torrefied fuels has been studied and compared to corresponding properties of coals and untreated biomasses [8–11], and some results are presented in Figures 3–4. The common conclusion is that the torrefaction temperature is a critical parameter influencing brittleness in order to obtain grindability behaviour similar to coal. Usually a significant improvement in grindability requires quite high torrefaction temperatures in the range of 290–300 °C. A reduction of grinding energy consumption by ten times for torrefied pine chips compared to untreated biomass has been reported at a torrefaction temperature of 300 °C [8]. The published studies do not, however, provide an exhaustive answer to the issue of how torrefied biomass pellets behave in a ball or roller mill when co-milled with coal at a PC boiler plant. The current studies usually comprise experiments performed with cutting or hammer mill type of equipment and with torrefied fuels rather than pelletised.

According to published estimates, it is possible to replace about half of the solid fuel with torrefied pellets in pulverised coal-fired combined heat and power plants. A prerequisite for this is that the torrefaction process is able to convert the biomass to a satisfactorily brittle solid fuel to be milled together with coal, in order to produce a fuel mix that fulfils the requirements of the PC boiler.

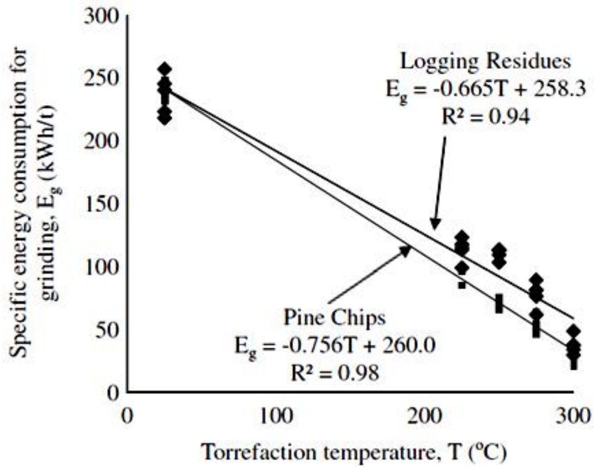


Figure 3. Effect of torrefaction temperature on the specific energy consumption for grinding of torrefied biomass [8].

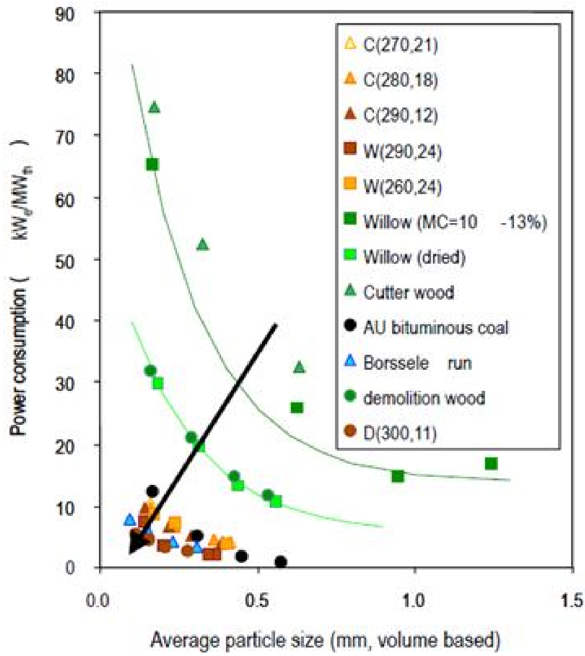


Figure 4. Grindability of various torrefied biomasses compared to coal and untreated biomasses [5].

2.3 Densification

Product densification allows torrefied biomass to be converted into a convenient energy carrier in terms of transportation, storage and handling, due to its uniform shape and size. The pelletisation process of woody biomasses is a commercial process, and the current global market volume of the wood pellet market is estimated to be about 16 Mt/a. The fundamentals of biomass pelletising have been studied with the aim of understanding the phenomena involved in densification [12–13]. The practical experience from the pelletisation of torrefied biomasses is still quite limited, but research and pilot-scale experiments are ongoing [14].

Besides pelletisation, producing larger size densified fuel chunks by briquetting is also possible. The briquettes are typically cylindrical pieces with a diameter of 50 to 80 mm, compared to the usual pellet diameter of 6–10 mm. Briquetting is mostly used for smaller-scale production schemes, as the capacity of a briquetting press is 1–3 t/h. Modern pellet plants may have an annual capacity of 500,000 t/a and the capacity of individual pellet presses is in excess of 5 t/h.

3. Commercial development

Commercial development of torrefaction is currently in its early phase. Several technology companies and their industrial partners are moving towards commercial market introduction. The current demand for torrefied biomass of utilities alone exceeds the production capacity that can be realised in the coming years by far. This puts a lot of pressure on the torrefaction developers, who need to scale up their technologies as soon as possible.

An overview of reactor technologies that are applied for torrefaction is presented in Table 1. All reactor technologies here are “proven technology” in other applications, such as combustion, drying or gasification [1]. Several torrefaction technology providers in Europe claim that they have reached commercial production. In North America there are also some interesting initiatives under development, which claim that they are in a commercial demonstration phase. A few shiploads of torrefied pellets have been reported to have been shipped to Europe by the US company New Biomass Energy. The company’s 80,000 t/a plant in Quitman, Mississippi is currently being expanded to over 150,000 t/a. The market is expected to move forward but the available public information is very limited, especially concerning the technologies used and volumes produced.

The current general view is that most of the demonstration plants have technical problems that have delayed their commercial operation. Several smaller pilot installations covering a wide range of different technologies are available at research institutes and universities, such as Energy research Centre of the Netherlands (ECN), the Spanish National Renewable Energy Centre (CENER) and BioEndev (Sweden). A few of the most advanced projects are briefly described in Table 1.

Table 1. Overview of reactor technologies and associated suppliers [1].

Reactor technologies	Torrefaction supplier
Rotary drum reactor	CDS (UK), Torr-Coal (NL), Bio3D(FR), EBES AG (AT), 4 Energy Invest (BE), Bioendev/ETPC (SWE), Atmosclear S.A.(CH)
Screw conveyor reactor	BTG (NL), Biolake (NL), Foxcoal (NL), Agri-tech producers (US)
Multiple Hearth Furnace (MHF)/TurboDryer	CMI-NESA (BE), Wyssmont (US)
TORBED reactor	Topell (NL)
Microwave reactor	Rotavawe (UK)
Compact moving bed	ECN (NL), Thermya (FR), Buhler (US)
(Oscillating) Belt conveyor	Stramproy Green investment (NL), New Earth Eco Technology (US)

3.1 Topell Energy

Topell Energy applies a TORBED reactor designed for effective gas/solid contact in various industrial applications. Topell started the construction of their first commercial torrefaction plant in Duiven, the Netherlands, in 2010. With a production capacity of 60,000 t/a, the plant was expected to start producing torrefied fuel pellets from biomass in early 2011 [15]. Some 7–10,000 t of torrefied biomass has been produced for milling and co-combustion tests for various customers. The plant is still in the commissioning phase and a new combustion unit will be operational in mid-2013.

The TORBED fluidised bed reactor, Figure 5, has a short retention time and high heat transfer efficiency. However, it requires a fairly small particle size (sawdust), contrary to moving bed reactors, which can accept normal-sized wood chips. This set additional requirements on the pre-treatment steps of biomass fuels. Topell standard feedstock originates from forestry residues and biomass from landscaping.

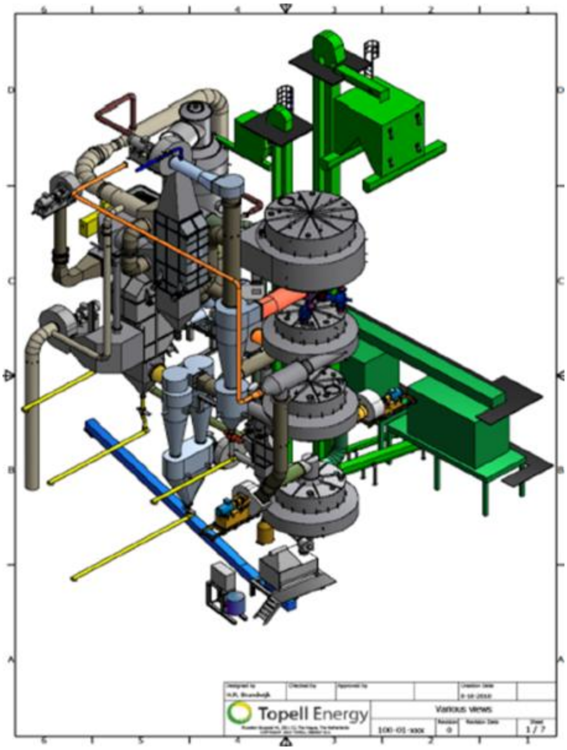


Figure 5. Topell Energy torrefaction reactor [15].

3.2 Thermya

In March 2010, French engineering company Thermya announced the commercialisation of its TORSPYD torrefaction process. The company is commissioning two industrial plants with a capacity of 20 000 t/a in Northern Spain and France [16]. The AREVA group has announced in 2012 the acquisition of the Thermya torrefaction process.

Thermya utilises a direct heated moving bed reactor to produce biocoal from biomass. The thermal treatment takes place in continuous counter current operation, where the solids flow down from the top to the bottom of the column and the torrefaction gas flowing upwards. The input requirements for the feedstock is 20% moisture content and crushing to minus 50 mm. Pre-dried crushed wood and wood chips are apparently torrefied in quite a mild condition to preserve 95% of the original biomass energy content.

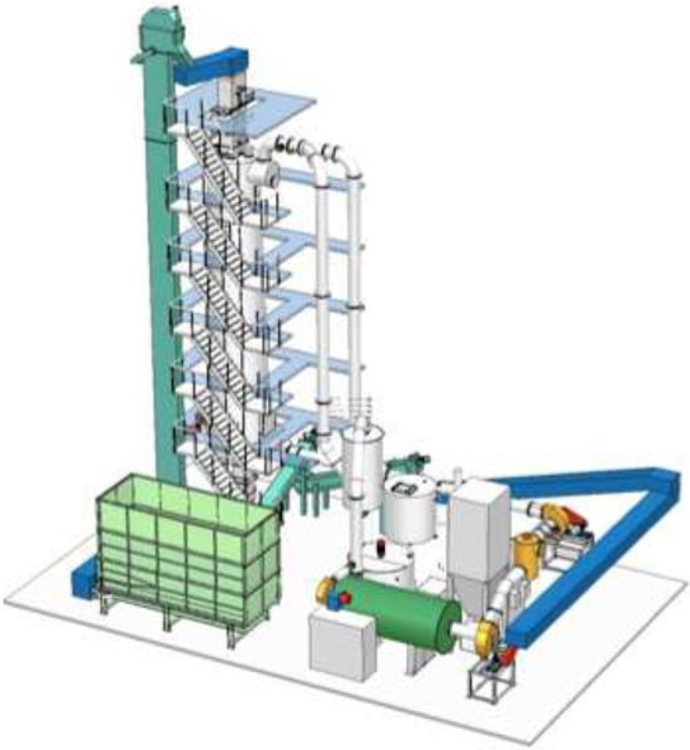


Figure 6. The Thermya torrefaction process layout [16].

3.3 ANDRITZ torrefaction processes

ANDRITZ has introduced two main torrefaction technology platforms focusing on small to medium-sized plants of 50,000–250,000 t/a, and large plants of up to 700,000 t/a [17]. The smaller concept, Figure 7, is based on an indirectly heated rotary drum reactor and briquetting of the torrefied biomass. Pre-drying of the biomass is done in a belt dryer. Flue gas for the torrefaction process and the dryer is produced by a grate-fired biomass combustor.

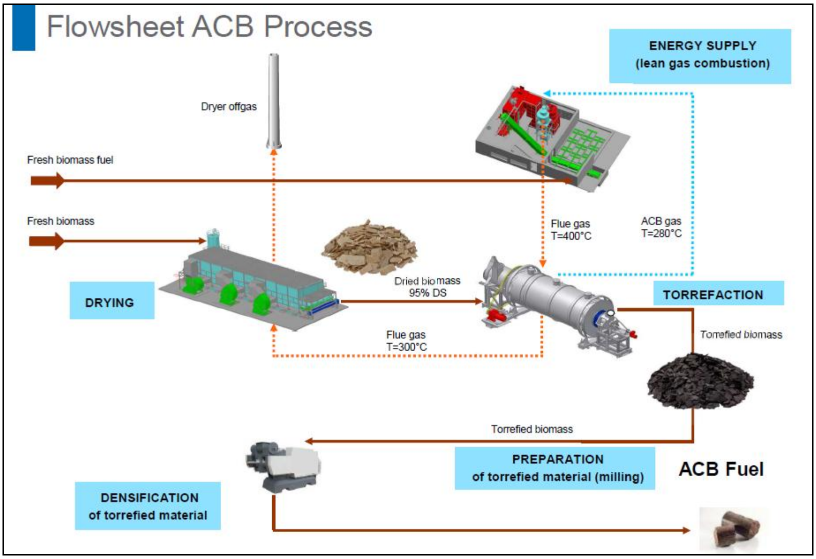


Figure 7. The ANDRITZ ACB torrefaction process [17].

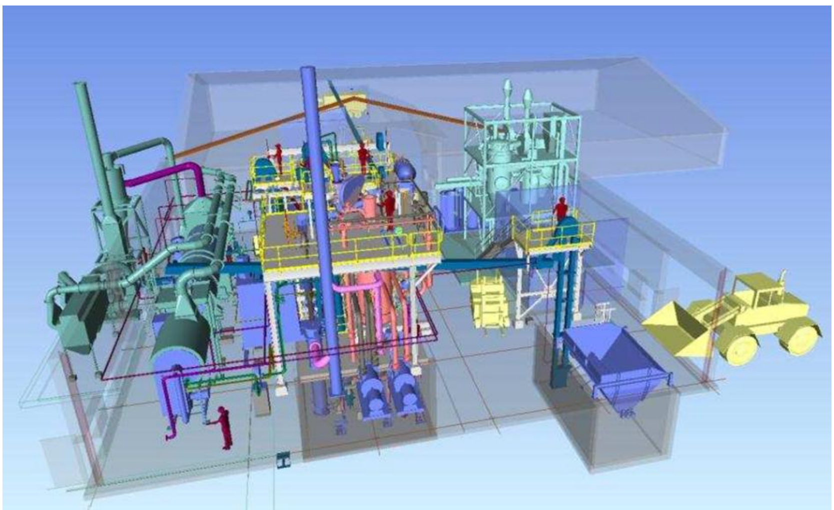


Figure 8. The ANDRITZ vertical reactor technology, demo plant [17].

ANDRITZ is developing the vertical reactor technology together with ECN and commissioned a demonstration plant in Denmark in 2012, Figure 8. ECN has a lot of experience of biomass torrefaction and has been operating a small pilot plant in research projects for several years. The process is a pressurised, directly heated moving bed reactor utilising conventional drying and pelletisation. Several hundred tons of torrefied biomass was produced since the autumn of 2012 in the 1 t/h demo plant.

3.4 Stramproy Green

Stramproy Green Technologies in the Netherlands has a torrefaction production plant in Steenwijk, the Netherlands, with a reported capacity of about 45,000 t/a [1, 18]. The torrefaction plant is integrated into a CHP plant and uses a vibrating horizontal bed reactor, Figure 9. Instead of normal pelletisation, Stramproy produces small pillow-shaped briquettes with roller presses using water and binder additives.

Figure 9. The vibrating bed reactor at Stramproy Green torrefaction plant [18].

4. Pilot tests with Finnish wood fuels

4.1 General objectives

Given the availability of torrefaction pilot facilities in Europe, it was decided in the planning phase of the concerned national torrefaction research project not to build and operate separate pilot equipment. At this stage it was considered more efficient to use the available knowledge and experience in testing various Finnish feedstocks for torrefaction. The primary aims were to have a good understanding of the behaviour of the selected wood fuels in torrefaction, to produce large enough quantities for further testing, and to transfer the available public know-how in the torrefaction community to the project partners. ECN was identified early on as the most suitable project partner having the required laboratory and pilot facilities, and a good deal of experience in torrefaction research work. ECN was thus granted the order to execute a test programme with Finnish wood fuels, which included preliminary laboratory-scale testing and pilot-scale test runs in the PATRIG torrefaction test rig. The description of tests, results and conclusions in the following sections is mainly based on the test report produced by ECN [19].

4.2 Description of test programme

A set of five wood fuels was chosen for preliminary laboratory -scale testing at ECN. The torrefaction behaviour was tested by means of Thermo-Gravimetric Analysis (TGA) and ECN's torrefaction batch reactor. The pelletising behaviour of the wood fuels was tested in a small-scale, single pellet Pronto-press. Based on these findings, two wood fuels were selected and torrefied in the PATRIG pilot-scale torrefaction plant at ECN, to produce several tonnes of materials under various torrefaction conditions. With the materials produced, pelletising tests were executed at the semi-industrial pelletising laboratory of CPM-Europe in Amsterdam.

TGA and batch tests were carried out for the five feedstocks to determine the torrefaction behaviour of the biomass, comprising:

- TGA tests at different torrefaction temperatures to determine the preferred torrefaction temperature for the batch tests.

- Five batch tests to produce small portions of torrefied materials from the materials and to determine the operating settings for the two materials to be processed in the PATRIG pilot rig.
- Determination of the mass and energy balance for the five batch tests, including proximate and ultimate analyses of the raw and torrefied materials.
- Small-scale Pronto-press tests with the torrefied materials produced in the batch reactor.

The pilot test programme comprised operation of the PATRIG pilot-scale torrefaction plant over two weeks, each week comprising approximately 75 hours on a 24-hour basis. Two wood fuels were selected for the pilot tests, including good quality wood chips produced from thinnings and crushed forest residue containing more bark and needles. Based on the results of the TGA, batch and Pronto-press tests, three operating temperatures were selected: 235, 245 and 255 °C. Semi-industrial scale pelletising tests were carried out with the materials produced in the PATRIG test rig. In total about 4300 kg of torrefied wood and forest residue chips were produced. Of this, about 1,500 kg of torrefied pellets were produced at CPM.

4.3 Test facilities

4.3.1 Batch reactor

The ECN's batch reactor is a vertical cylinder that can be filled from the top with the feedstock to be tested, Figure 10. The reactor is operated as a fixed-bed reactor which is flushed with gas (nitrogen). Desired temperatures in the reactor are achieved to a major extent by pre-heating the nitrogen gas and to a minor extent by externally heating the walls. When the desired residence time is achieved, the reactor is cooled down by shutting off the external heating and the heater of the gas while maintaining a continuous gas flow. The reactor is divided into three zones, separated by perforated plates. All temperatures, gas flows and pressures are logged, allowing off-line data analysis. For all the experiments, the residence time was fixed at 30 minutes.

Figure 10. The batch reactor at ECN.

4.3.2 Pronto-press

In the ECN's Pronto-press, a single pellet is made under accurately controlled temperature and pressure conditions. The press is filled with a small amount of material, which is compressed. The density of the single pellet produced gives an indication of how well the material can be pelletised.

4.3.3 Torrefaction pilot plant PATRIG

In order to study torrefaction on a scale which is representative for industrial-scale torrefaction units, ECN has designed, erected and commissioned a 50–100 kg/h torrefaction pilot plant called PATRIG. Figure 11 shows this three storey-high pilot plant. On the top floor, the biomass is fed to the torrefaction reactor via conveyor belts and a sluicing system. The directly heated moving bed torrefaction reactor is situated on the first floor. Here the biomass is heated and torrefied, using the recycled torrefaction gases (torgas). On the ground floor the torrefied material is extracted and stored in storage bins.

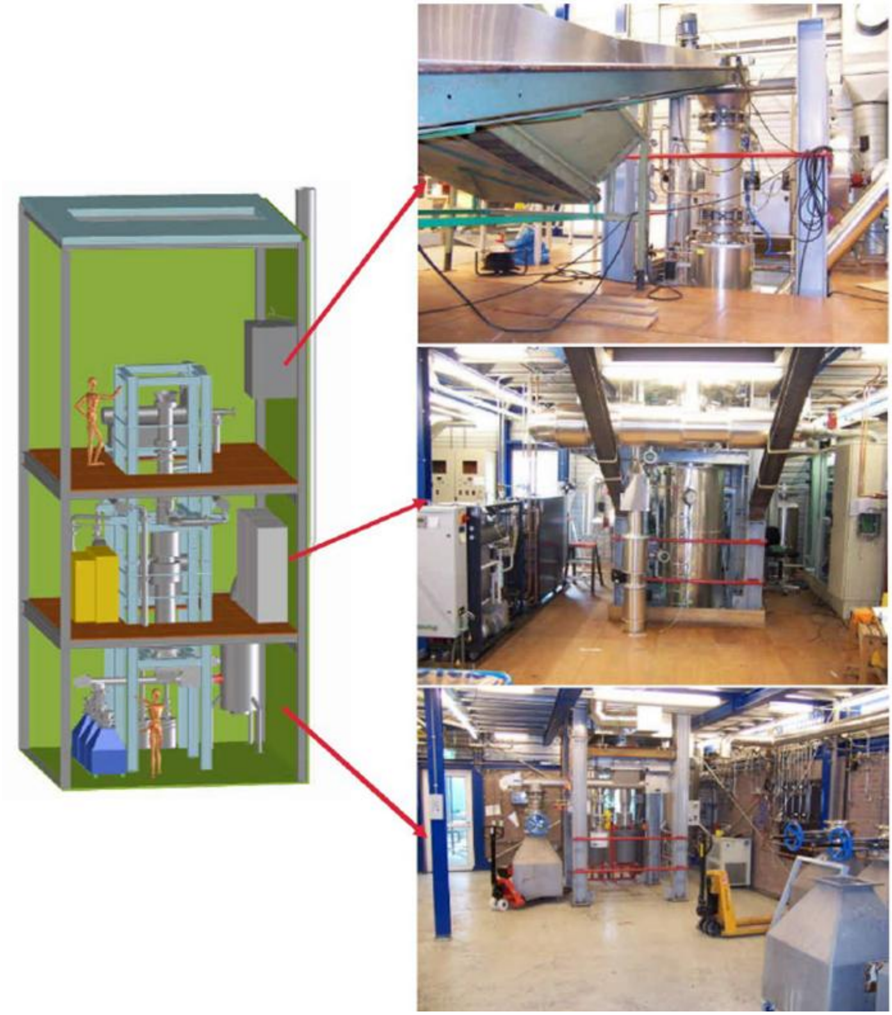


Figure 11. Overview of ECN's 50–100 kg/h torrefaction pilot plant PATRIG.

4.3.4 Semi-industrial pelletising

For the semi-industrial scale work, a pelletising laboratory of CPM, a hammer mill and a semi-industrial pellet mill are available. The ring dye pellet press is shown in Figure 12.

Figure 12. CPM semi-industrial ring dye pellet press.

The materials are fed into the hammer mill and the milled material is pneumatically transported to a mixing bin above the pellet mill. In the mixing bin, water and/or binder can be added to the grinded material. From the mixing bin, the material is fed into the pellet mill and is pelletised. The pellets produced are transported by means of a conveyor belt to a cooler, in which the pellets are cooled. After cooling, the dust is removed and the pellets are transferred to big-bags.

4.4 Biomass feedstocks and preparation

For the preliminary laboratory torrefaction work, VTT delivered five different biomass feedstock samples to ECN:

1. Pine chips (stem wood)
2. Willow chips
3. Spruce bark (crushed)
4. Whole tree wood chips
5. Forest residue (crushed).

Five samples were used in the TGA and the batch tests. The torrefied samples produced in the batch test were tested for pelletising behaviour in the Pronto-press.

The feedstocks chosen for the pilot tests were:

- Whole tree wood chips produced from thinnings, mainly pine trees. Good quality wood chips containing mainly stem wood and very little bark.

- Forest residue produced from mixed wood by crushing tops, branches and green parts. Due to the requirements of the PATRIG test rig, the crushed forest residue was sieved to a particle size of between 8 and 32 mm. This action obviously increased the share of the woody constituents and decreased that of needles and bark.

About 3,000 kg of both fuel grades were produced and dried at the Kokemäki heating station in Western Finland. The drying was carried out outdoors in fuel stacks placed on a grating. Warm air from the heating plant was used to dry the biomass chips to a moisture content of below 20%. The fuels were packet in large bags, approximately 20 of each grade, and transported to the Netherlands for torrefaction. The biomass feedstocks and products are shown in Figure 13.

Figure 13. Feedstocks and products of the pilot tests in PATRIG torrefaction rig.

4.5 Results and discussion

4.5.1 Small-scale tests

In this chapter, an overview is given of the results obtained with TGA, batch reactor and Pronto-press.

Five TGA tests per sample were conducted at torrefaction temperatures ranging from 225 °C to 285 °C. The results are presented in Table 2 and in Figure 14. The residence time at torrefaction temperature for all tests was 30 minutes.

Table 2. TGA results for the biomass samples.

Test no	Temperature (°C)	Mass yield (wt% dry basis)				
		Forest residue	Whole tree	Spruce bark	Pine chips	Willow chips
1	225	93.78	93.53	91.41	94.53	93.47
2	240	89.80	88.62	87.91	91.20	88.17
3	255	84.13	82.01	83.68	85.93	81.64
4	270	77.10	74.38	78.34	78.36	74.72
5	285	68.50	65.27	72.03	67.88	65.88

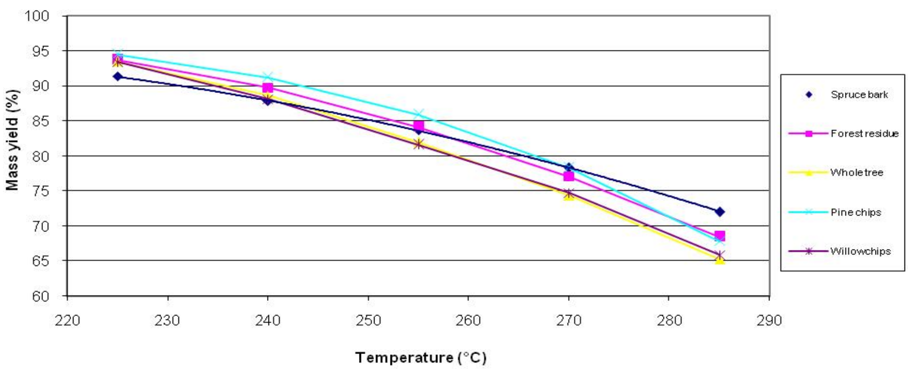


Figure 14. Degradation curves for the biomass samples.

Previous investigations showed that between 15–20 wt% is the optimum mass loss for torrefaction of dry woody materials, assuming that the hemicelluloses content of the materials is approximately 20 wt%. Figure 14 shows that the differences between the five biomass samples tested are relatively small and that 15–20% mass loss is realised for all materials at a temperature of between 250 and 260 °C. Therefore, from the TGA results 250–260 °C was found to be the optimum torrefaction temperature range for all the materials.

Based on the TGA results, batch reactor experiments with five biomass samples were carried out at three selected temperature levels:

- for whole tree chips: 235, 245 and 255 °C
- for forest residue chips: 245 and 255 °C
- for willow chips, crushed bark and pine chips: 255 °C.

The torrefaction temperatures for forest residue and whole tree chips were chosen at the lower end of the torrefaction regime, because experience showed that pelletising mildly torrefied material is easier than pelletising severely torrefied material.

Table 3 presents the results of the proximate and ultimate analyses of the biomass feedstocks and the torrefied materials produced in each batch experiment.

Table 3. Proximate and ultimate analyses of raw materials and torrefied samples.

Fuel	Ash % (550°C) (db)	H_2O % (105°C) predried	Volatiles % (db)	Fixed carbon % (db)	C % (db)	H % (db)	N % (db)	O % (db)	HHV kJ/kg (db)
Whole Tree	0.5	0.5	83.2	15.8	49.7	6.2	0.17	43.6	19967
Whole Tree-batchr. 235°C	0.5	<0.1	80.4	19.1	51..5	6.1	0.19	41.8	20986
Whole Tree-batchr. 245°C	0.7	<0.1	77.9	21.4	52.2	6.0	0.23	45.9*	21007
Whole Tree-batchr. 255°C	0.7	<0.1	74.4	23.9	53.6	5.9	0.30	39.5	21586
Forest Residue	1.3	0.3	80.5	17.9	49.8	6.2	0.30	42.9	20206
Forest Residue-batchr.255°C	1.2	<0.1	77.1	21.7	52.2	6.0	0.31	40.4	20959
Forest Residue-batchr.255°C	0.8	<0.1	76.3	22.9	53.2	6.0	0.22	44.3*	21354
Crushed Bard	3.6	<0.1	69.4	27.0	51.9	5.7	0.45	41.0	20459
Crushed Bark-batchr.255°C	4.2	<0.1	62.4	33.4	56.7	5.2	0.52	38.7	21990
Pine chips	0.3	<0.1	83.2	16.6	50.9	6.6	0.09	43.6	20337
Pine chips-batchr.255°C	0.3	<0.1	78.8	20.9	53.3	6.4	0.09	41.1	21207
Willow chips	1.8	2.4	79.8	16.0	49.0	5.8	0.53	43.1	19861
Willow chips-batchr.255°C	2	<0.1	73.5	24.5	53.1	5.7	0.59	38.8	21370

* = outlier in analysis

Mass and energy yields of the batch tests were calculated for the torrefied materials. The mass yield varied between 81 and 87%. With the torrefaction temperatures used, between 88 and 91% of the chemical energy remains in the torrefied wood fuel. For all samples, the calculated energy yields obtained in the batch tests were higher than the mass yields, indicating energy densification due to torrefaction.

Exothermal behaviour during the batch torrefaction tests was studied using time-temperature graphs. For most of the biomass feedstocks, a slight exothermicity was observed at the higher torrefaction temperature of 255 °C. The most pronounced exothermal behaviour was observed for willow chips. The reasons behind the difference in exothermic behaviour between different biomass species are still not well understood. It is presumed that it might be due to differences in their carbohydrate content and/or structural differences.

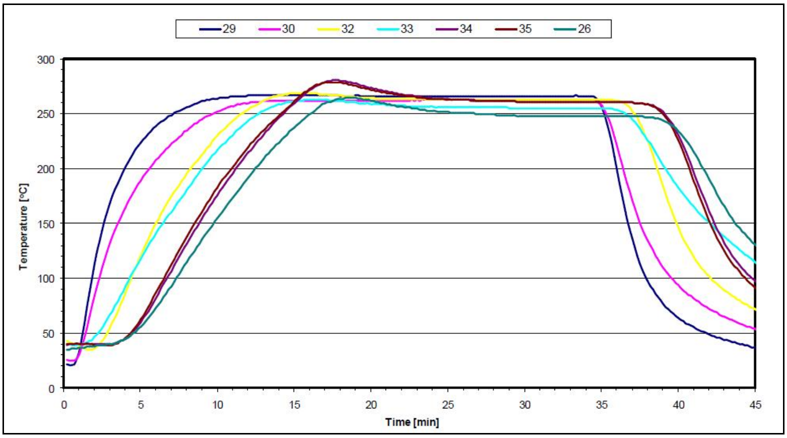


Figure 15. Time-temperature graph for willow chips at set point 255 °C. An overshoot of the recorded temperatures can be observed, indicating an exothermic behaviour.

In order to have an indication of the pelletising behaviour of the torrefied materials, single pellet Pronto-press tests were executed to see if there is a chance that the torrefied materials can be pelletised on an industrial scale. Based on these small-scale Pronto-press tests, final decisions were taken on the torrefaction temperature level in the PATRIG pilot plant. The torrefaction temperature influences the pellet quality and by determining the pelletising behaviour before the execution of the PATRIG run, one can choose a temperature level in PATRIG that gives the best chance of good quality pellets.

In the Pronto-press, a single pellet is made under controlled conditions. The temperature and pressure are chosen at a level comparable with the levels in an industrial pellet mill. The duration of pressing is one minute, this being much longer than in a pellet mill. The density of the single pellet produced gives an indication of how well the material can be pelletised. The results are summarised below regarding prediction for pelletising:

- Whole tree chips 235°C possible
- Whole tree chips 245°C difficult
- Whole tree chips 255°C more difficult
- Forest residue 245°C large uncertainty, no prediction
- Forest residue 255°C difficult
- Willow chips 255°C difficult
- Crushed bark 255°C impossible
- Pine chips 255°C difficult.

Based on the results, it was concluded that neither torrefied whole tree chips nor forest residue chips are easy to pelletise, but that the chance of getting good pellets increases when the torrefaction temperature is low. Therefore, the torrefaction temperature during the PATRIG runs was chosen to be as low as practical. These low temperatures are also favourable to the prevention of excessive exothermic reactions.

4.5.2 Conclusions of the small-scale tests

For the results of all small-scale tests, the following conclusions can be drawn:

- The optimum torrefaction temperature range for whole tree chips, forest residue, spruce bark and pine chips is estimated to be 250–260 °C.
- Torrefied materials have a higher energy density than the raw materials. This is explained by the higher loss in mass than in energy. At the estimated optimum torrefaction temperature, the energy yields are higher than 87%.
- Whole tree chips, spruce bark and willow chips are slightly exothermal. Forest residue and pine chips are hardly exothermal. For willow chips a slightly lower torrefaction temperature should be applied to avoid exothermic reactions that might lead to a temperature rise during the torrefaction process. For pine chips, a higher temperature can be applied.
- The chance of getting good pellets increases when the torrefaction temperature is low.

Based on these results, it is expected that both forest residue and whole tree chips can be torrefied in PATRIG without a significant temperature increase, but that pelletising these materials will not be a straightforward process. Especially at higher torrefaction temperatures, pelletising could be difficult. Therefore, relatively low torrefaction temperatures will be chosen for the PATRIG runs. Semi-industrial scale tests will show the pelletising possibilities.

4.5.3 PATRIG production tests

The purpose of the PATRIG test runs was to produce torrefied materials for pelletising tests and to deliver the produced pellets and the remaining torrefied materials to VTT for further testing in Finland. In this section, the findings during the PATRIG production runs are reported.

The pilot testing started with the good quality whole tree wood chips. Based on the results of the TGA, batch and Pronto-press tests, three operating temperatures were selected: 235, 245 and 255 °C. It was soon observed that the set point of 235 °C (torgas inlet temperature) was very low and the tests were continued at higher temperatures. The total duration of the run was 68.7 hours. Little or no exothermicity was found at these temperatures. The whole tree chips production run went smoothly.

Slightly higher temperatures were chosen for the forest residue production run: 240, 250 and 260 °C. The total duration of this run was 70.6 hours and the test proceeded smoothly.

Figure 16 shows the operating conditions. The torgas inlet temperature together with three thermocouple readings at different levels in the torrefaction reactor are shown. The figure shows slightly higher temperatures in the reactor compared to the torgas inlet temperature. This illustrated the (limited) exothermal behaviour of the material under the given torrefaction conditions.

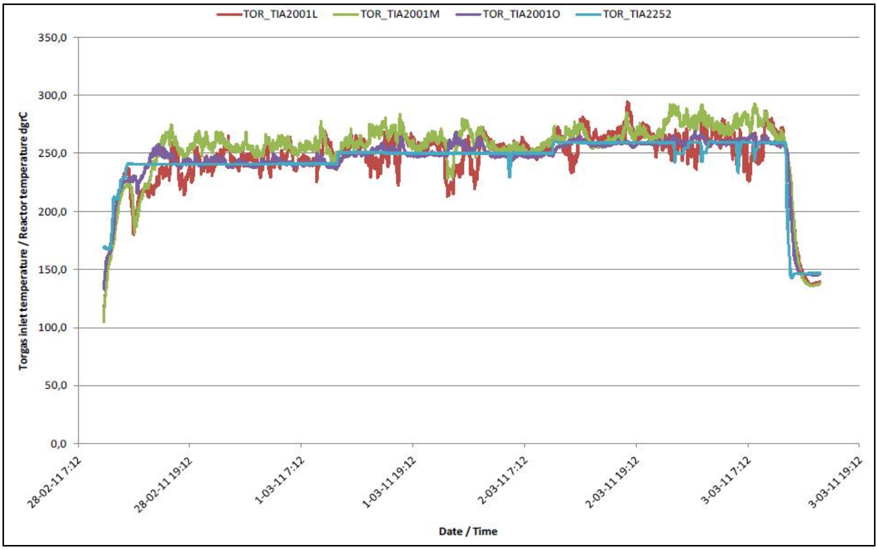


Figure 16. Torgas inlet temperature (TIA2252) and three reactor thermocouples (TIA2001L, TIA2001M and TIA2001O) in ^{o}C during the run with forest residue chips.

The mass balance of the run with “forest residue” chips is summarised in Table 4. The mass of solid inputs and outputs was determined from weighing the in and outgoing materials over the stable periods at the different set points. The torgas quantity (without biomass moisture) was determined by calculating the difference in weight between the dry biomass in and the torrefied biomass out for the stable periods at the three set points.

Table 4. Mass yields of the torrefaction runs in the PATRIG pilot plant.

Torrefaction temperature, °C	Mass yield, %	
	Whole tree wood chips	Forest residue chips
235	91	
245	81	
255	77	
240		91
250		83
260		77

4.5.4 Conclusions of PATRIG production runs

Both materials were easy to torrefy, and stable conditions could be maintained during the whole production run. At the chosen operating temperatures, both materials showed hardly any exothermic behaviour. For both materials, the mass yield varied from 91 to 77%, but for forest residue chips a 5 °C higher temperature was imposed to reach these mass yields (240/260 °C versus 235/255 °C).

4.5.5 Comparison between small-scale tests and pilot-scale runs

The mass yields of whole tree chips and forest residue chips found during the PATRIG runs can be compared with the yield found with the TGA and batch reactor tests. The results of the forest residue chips are given in Figure 17. The graph shows that there were differences between the results of the batch reactor tests, the TGA tests and the PATRIG runs, but that the differences can be fully explained by the inaccuracy in the determination of the moisture content of the fresh material. It is concluded that the results are reliable, but that more attention must be given to the determination of the moisture content.

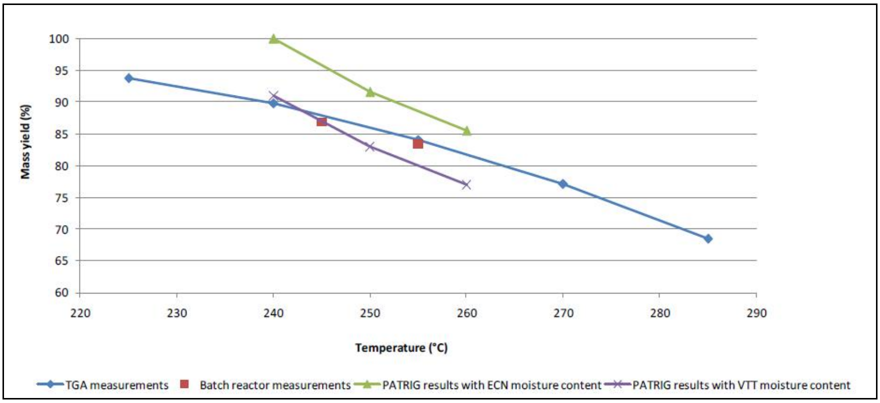


Figure 17. Mass yields of forest residue chips, determined with TGA, batch reactor tests and PATRIG runs.

4.5.6 Semi-industrial pelletising tests

Semi-industrial scale pelletising experiments were performed at CPM-Europe in Amsterdam, using the torrefied materials produced at PATRIG:

- Whole tree chips, torrefaction temperatures of 235, 245 and 255 °C.
- Forest residue chips, torrefaction temperatures of 240, 250 and 260 °C.

The materials were milled in a hammer mill and pelletised in a small-scale industrial pellet press.

The results of the tests show that it is possible to make pellets from the torrefied wood fuels, but pelletising is not straightforward. In general, pelletising low temperature torrefied wood fuel is easier than pelletising wood fuels torrefied at higher temperatures. Adding water is always necessary and in some cases a binder is needed as well. The best quality pellets were produced with wood and forest residue chips torrefied at 240–245 °C. Binders (starch, flour) were used for pelletising forest residue chips torrefied at 250 and 260 °C to obtain reasonable pellet quality.

All the torrefied materials were easy to grind. Power consumption for milling ranges from 10–15 kWh/t. The power consumption of pelletising was 70–80 kWh_e/t for torrefied whole tree chips, and around 90 kWh_e/t for torrefied forest residue chips.

4.6 Overall conclusions

Based on the results from small-scale TGA torrefaction tests and Pronto-press pelletising tests, the torrefaction temperatures of the different materials were determined to be 235, 245 and 255 °C for whole tree chips, 240, 250 and 260 °C for forest residue chips, and 255 °C for wood chips (pine), willow chips and crushed bark (spruce). Batch reactor tests and PATRIG production runs confirmed that with the torrefaction temperatures mentioned, good quality torrefied materials were produced, except for whole tree chips torrefied at 235 °C. Here the torrefaction temperature was too low. Further, it was confirmed on a semi-industrial scale that good pellets can be produced from these materials except for torrefied forest residue chips torrefied at 260 °C. Overall it can be concluded that torrefied whole tree chips and forest residue chips can be pelletised, provided that the torrefaction temperature is no higher than 250 °C.

5. CFD modelling of torrefied wood co-firing with coal in a pulverised coal-fired furnace

5.1 Introduction

Computational Fluid Dynamics (CFD) was applied to simulate the co-firing of torrefied wood biomass (TF) with coal in a (normally) pulverised coal-fired furnace [20]. The goal of the work was to investigate the feasibility of the above-mentioned fuels to replace part of the coal from the combustion and furnace process. Torrefied biomass shares of up to 50% by weight (approx. 40% by energy) were considered, referring to the findings in the above described co-combustion tests.

5.2 Modelling approach

The commercial CFD code Fluent 12.1 equipped with VTT's sub-models for gas phase as well as heterogeneous (coal, TF) combustion was used in simulations. A brief listing of the relevant sub-models is shown in Table 6. Pulverised coal combustion was modelled with the particle sub-model developed earlier at VTT in cooperation with Fortum.

A sub-model for the combustion of torrefied biomass particles was developed in a different context, based on a similar model for pulverised biomass as well as on experiments and a parameter fitting procedure performed by Tolvanen & Raiko [21]. According to the model, the torrefied biomass particle undergoes drying, devolatilisation and char combustion with decreasing density. The initial density was derived by fitting a drop tube reactor data from ref. [21].

Table 5. CFD sub-models used in simulations.

Turbulence	Standard k-ε
Radiation	Discrete Ordinates
Turbulence-chemistry interaction	Eddy Dissipation Concept (EDC), VTT version
Gas phase chemistry	3-step global scheme with CO and H_2 as intermediate species
Fuel particles/droplets	Lagrangian approach Coal: Fortum/VTT pulverised coal combustion model TF: Fortum/VTT TF particle comb. model derived and modified from Tolvanen & Raiko [21]
NO_x	Fortum/VTT EDC based NO_x sub-model for pulverised fuel combustion

5.3 Furnace simulation

The process simulated here is a pulverised coal-fired furnace of tangential firing/corner firing type. The full load of the furnaces is 275 MW_{fuel}. It is equipped with twelve low NO_x coal burners on three levels, eight gas/oil burners on two levels below and above them, and an over-fire air system (OFA) for NO_x control.

The computational domain consists of burners, air nozzles and the furnace itself. A superheater region is included as far as the beginning of the second pass. The volume is divided into a mesh of 1.6 million cells for simulations.

5.4 Fuel properties and initial conditions

There are two different fuels considered in the simulations: coal and torrefied wood biomass. Coal and torrefied biomass are assumed to be pulverised together in coal mills and fed to the coal burners as a mixture.

The torrefied biomass prepared for the co-combustion tests in Japan was used in the simulations as well. Fuel properties determined in the combustion tests were used in the simulation work and initial particle density was fitted to the experimental results of ref. [21]. Milling tests showed that coal mill performance (particle fineness) degrades as the share of torrefied biomass pellets increases in the fuel mixture. This is taken into account in the coal and torrefied biomass co-firing cases. Particle size distributions are estimated based on the milling tests and plant data. Coal and torrefied biomass fuel properties are presented in Table 6 and particle size distributions in Figure 18.

Table 6. Fuel properties of coal and torrefied biomass (TF).

	Coal	TF
Moisture (wt%)	9.6	6.7
Ultimate analysis (wt%, dry)		
C	71.8	53.2
H	4.8	5.8
O	9.1	40.5
N	2.2	0.2
S	0.4	0.0
ash + others	11.7	0.4
Proximate analysis (wt%, dry)		
Volaties	35.7	82.5
Char	52.6	17.1
FR (fuel ratio	1.47	0.21
LHV (MJ/kg)	24.5	18.4

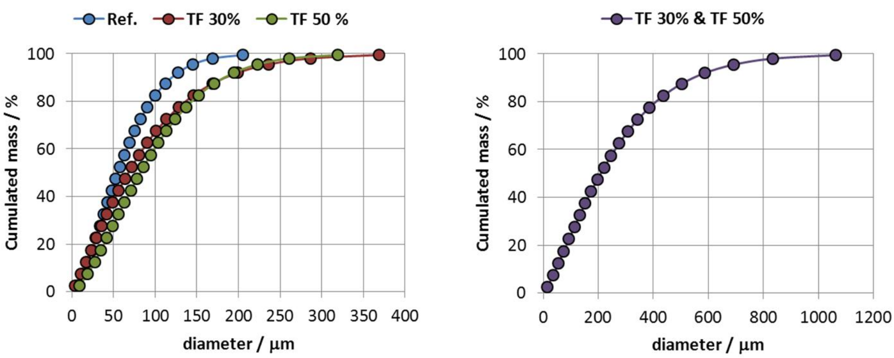


Figure 18. Particle size distributions of coal (left) and torrefied biomass (right) used in simulations.

5.5 Simulated cases

In total four main cases were simulated in this work: one coal combustion case for reference and three torrefied biomass and coal co-firing cases. In the following, a brief description is given for each. Case input conditions are compared in Table 7.

Case: Coal 100wt%

- Reference case, coal combustion, full furnace load, all coal burners in operation, cooling air from oil/gas burners, SR (air to fuel stoichiometric ratio) burner 0.8, SR burner zone (incl. cooling) 1.0, SR total (incl. OFA) 1.3 (flue gas O_2 4.3 vol%, wet).

Case: TF 30 wt%

- TF & coal co-firing case, share of torrefied biomass 30% by weight (24% by energy), full furnace load, degraded coal particle fineness (see Figure 18), all coal burners in operation, cooling air from oil/gas burners, SR burner 0.8, SR burner zone (incl. cooling) 1.0, SR total (incl. OFA) 1.3 (flue gas O_2 4.4 vol%, wet).

Case: TF 50 wt%

- TF & coal co-firing case, share of torrefied biomass 50% by weight (43% by energy), full furnace load, degraded coal particle fineness (see Figure 18), all coal burners in operation, cooling air from oil/gas burners, SR burner 0.8, SR burner zone (incl. cooling) 1.0, SR total (incl. OFA) 1.3 (flue gas O_2 4.4 vol%, wet).

Case: TF 50 wt%, fine coal

- Same as previous TF 50% case, but coal is assumed to preserve its original fineness in milling (e.g. separate milling of torrefied biomass pellets). No change in TF particle size.

Table 7. CFD case comparison.

	Coal 100%	**TF 30% (mass basis)**	**TF 50% (mass basis)**
Fuel input (MW) coal (%), energy basis TF (%), energy bases	275 100 0	275 76 24	275 57 43
Fuel flow rate (kg/s)	11.2	12.1	12.8
Total Stoichiometric Ratio SR coal burner SR burner zone	1.3 0.8 1.0	1.3 0.8 1.0	1.3 0.8 1.0
Flue gas O_2 (vol-%, wet)	4.4	4.4	4.4
Air flow rate (kg/s)	123.5	121.2	119.3
Flue gas flow rate (kg/s)	133.3	132.2	131.3

5.6 Simulation results

5.6.1 Combustion in general, temperature, heat transfer

The main observation from the simulation results is that combustion does not change that much on a furnace scale compared to pure coal. As the torrefied biomass share increases, the flame stability seems to fade slowly as a consequence of larger average particle size decelerating ignition. The hottest spots move a little further away from the burner opening. According to the results, however, flames are still stable with the torrefied biomass shares of up to 50% at full burner load. At the same time, evaporator heat transfer is weakened marginally and the furnace exit gas temperature at nose level tends to rise by some 0–20 degrees. Assuming an original coal fineness in torrefied biomass of 50 wt%, case flame stability is excellent. Heat transfer is even enhanced compared to pure coal firing.

Temperature contours and wall incident radiation are compared for two cases, and evaporator heat transfer and furnace exit gas temperature (FEGT) for each case in Figures 19–21.

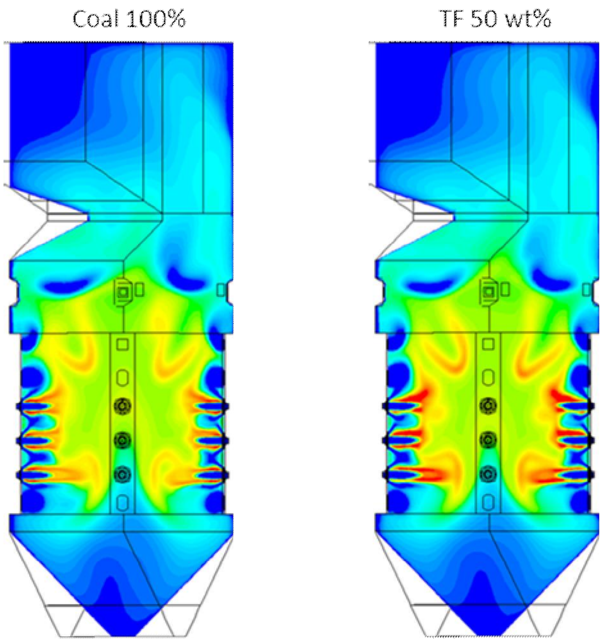


Figure 19. Temperature contours from one diagonal section of the furnace.

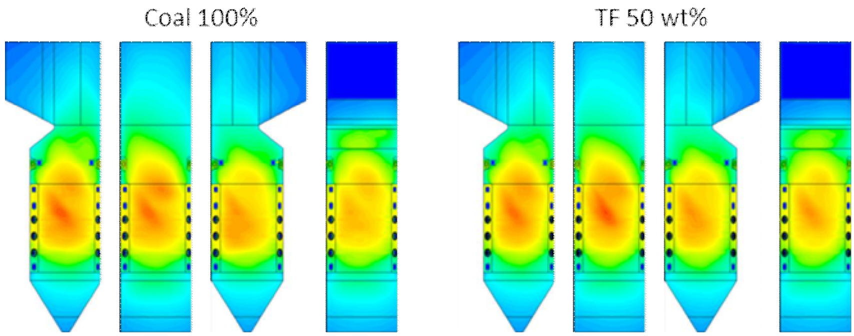


Figure 20. Wall (left, front, right, rear) incident radiation.

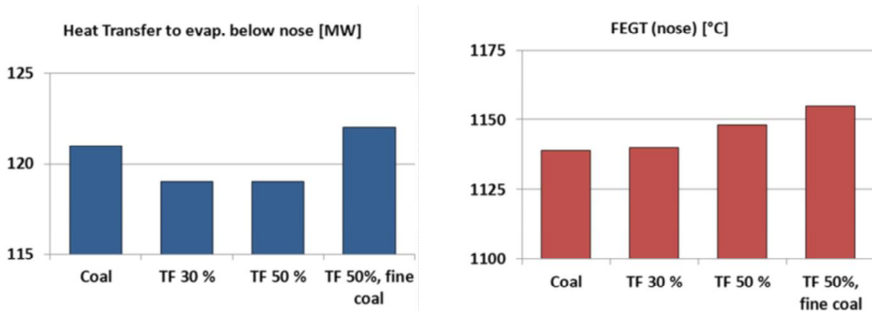


Figure 21. Predicted evaporator heat transfer (left) and predicted Furnace Exit Gas Temperature (at nose level).

5.6.2 Burnout, unburned carbon and CO

The simulation results clearly indicate that (solid) combustion efficiency remains at almost the same level in all co-firing cases compared to pure coal combustion There is, however, a predicted rise in fly ash unburned carbon (UBC) in torrefied biomass 30% and torrefied biomass 50% cases, as a direct consequence of increased coal particle size due to degrading mill performance, as torrefied biomass pellets are added to the mills. Combustion efficiency and fly ash UBC are plotted in Figure 22.

Coal mainly contributes to UBC, while torrefied biomass contains a lot of volatiles and only a small fraction of inorganic ash. In addition, biomass char is quite reactive. Reduced ash flow, for example about 60% of the original with the torrefied biomass share of 50 wt%, explains the good combustion efficiency despite the increase in UBC.

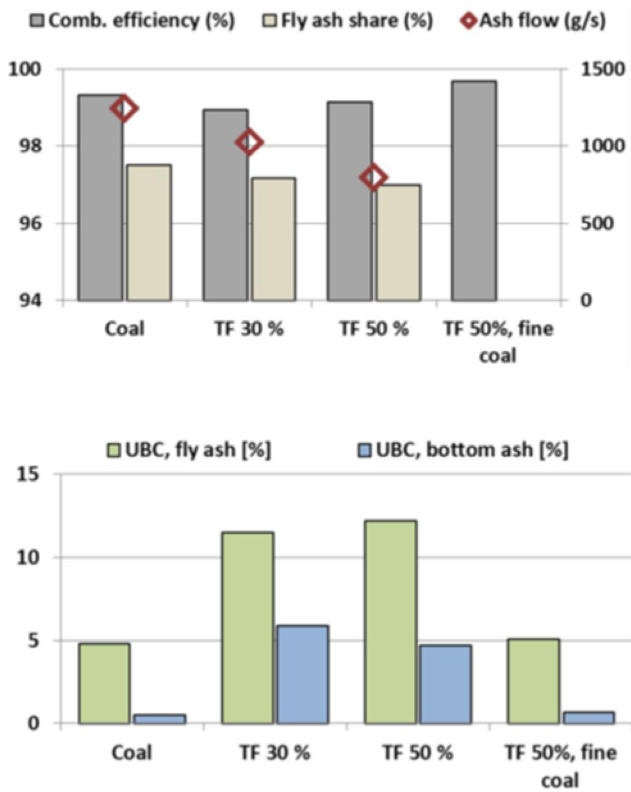


Figure 22. Predicted solid combustion efficiency and fly ash UBC.

The UBC level in co-firing is predicted to be very comparable to a pure coal case if milling performance can be maintained, as can be seen in TF 50 wt% fine coal case assuming separate crushing of the torrefied biomass pellets.

In all torrefied biomass co-firing cases, the nose level CO concentration is predicted to be lower than in the coal combustion case, but in all but one (the fine coal case) the outlet concentration is then higher by contrast. This difference is explained by continuing char particle burnout in the superheater zone (also contributing to higher UBC). Simulated nose level and domain outlet CO concentrations are shown in Figure 23.

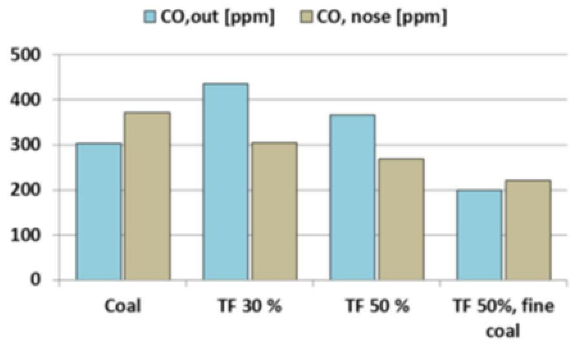


Figure 23. Predicted CO concentrations (at nose level and at domain outlet).

5.6.3 Simulated NO_x emissions

According to the simulation results, NO_x emissions would decrease in the modelled co-firing cases compared to coal combustion due to lower fuel nitrogen content in torrefied biomass. Emission reductions of up to 20% are predicted in the TF 50 wt% fine coal case. Simulated NO_x emission values are plotted in Figure 24.

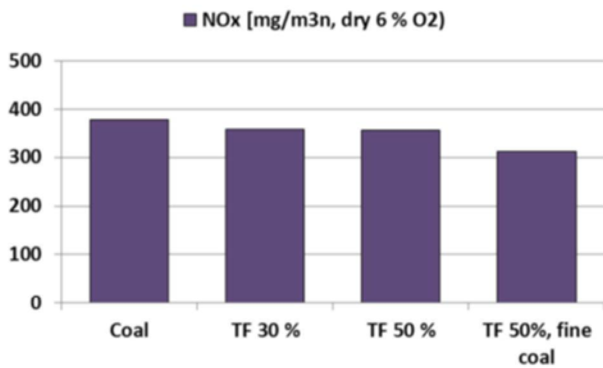


Figure 24. Predicted NO_x emission in simulated cases.

5.6.4 Corrosion and fouling tendencies

The simulation results indicate that the risk of fouling and corrosion remains low at the main combustion zone in all simulated co-firing cases. Unreacted fuel is transported to the centre of the furnace. Evaporator walls are well protected by combustion/cooling air so that there is only a small concentration of particles and practically no unburned (CO) gases in the near wall region.

Instead, some problems might arise in the superheater region with biomass originated ash and inorganic gaseous species involved, especially as the gas temperature is predicted to rise in the upper part of the furnace during co-firing.

5.7 Conclusions

Based on the CFD simulations, the following conclusions can be drawn.

From the combustion point of view, it seems feasible to replace coal by torrefied wood biomass in the unit investigated, with shares of up to 50% by weight. Flame stability could be an issue with even higher shares of torrefied biomass or partial burner load operation with notable torrefied biomass content in fuel.

There should be no drastic change in furnace heat transfer, although a small reduction in evaporator heat transfer rate (< 5%) might be expected. It is anticipated that the furnace exit gas temperature before the superheater region will rise slightly during co-firing.

According to the model, torrefied biomass co-firing is characterised by:

- combustion efficiency comparable to pure coal firing
- reduced total ash flow
- increased unburned carbon in fly ash, presuming that coal mill performance degrades along with the addition of torrefied biomass.

Combustion efficiency and unburned carbon can be positively affected by improving mill performance if possible, or by applying separate crushing for torrefied biomass, for example.

The actual CO emission trend remains unclear due to modelling uncertainties, but no drastic increase is predicted. NO_x emissions are reduced when increasing the share of biomass-based fuel. A reduction of up to 20% might be possible in torrefied biomass co-firing.

Evaporator wall fouling/corrosion problems are not expected to increase in the furnace investigated. The superheater region might be more vulnerable in that sense with the simulated rise in furnace exit gas temperature.

6. Storage and handling properties of torrefied wood pellets

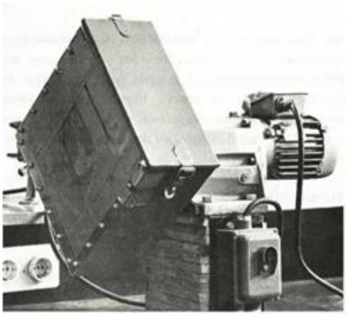
Conventional wood pellets can be considered a commodity fuel, having been on the market since the 1980s. Their utilisation ranges from small-scale domestic heating to large-scale co-firing in PC boilers to replace fossil fuels. Logistics, storage and handling of the wood pellets have achieved a fairly well defined and controlled practice. Common expectations on torrefied wood pellets regarding storage and handling properties have been high. Expected enhanced durability and hydrophobicity have even suggested open air storage similar to coal. Little information is, however, available on the physical properties of torrefied wood pellets, although these issues have a significant influence on the economics, safety and health issues of the industrial utilisation of these fuels. Some basic small-scale experimental work was conducted in the national research programme to compare torrefied wood pellet properties with conventional wood and straw pellets. These experimental methods have been described elsewhere [33] but are reproduced here for clarity.

6.1 Test procedures and materials

Physical properties of the torrefied pellets and reference pellets were determined with regard to mechanical durability, compression strength and bulk density. Moisture content and heating values were also analysed. Climate tests included equilibrium moisture content (EMC) determination, immersion tests and rain exposure tests in laboratory conditions. Standard test procedures were used when available. When possible, some durability tests were carried out in connection with EMC and rain exposure tests.

The mechanical durability of a densified fuel gives an indication of the fuel's ability to retain its form during transport and handling processes without going to pieces. Durability was measured according to the existing standard (EN 15210-1) which is applicable for fuel pellets. The durability value gives the mass proportion of the sample, which remains intact after the removal of fine broken pieces (fines which pass through a 3.15 mm sieve). For conventional wood pellets, the minimum normative durability classification is equal to or greater than 97.5% [22].

Although not existing as a standard, pellet hardness is a commonly used measurement to describe a pellet's resistance to a static force applied at right angles to the radial axis of the pellet. A pellet compression strength tester (manufactured by Amandus Kahl GmbH & Co. KG, Germany) was used for this measurement. The test was repeated ten times for each sample type (i.e. ten pellets of each sample) and the average value in kilogram equivalency is reported. Being a static force measurement, the results are given in kg. The test equipment used is shown in Figure 25.



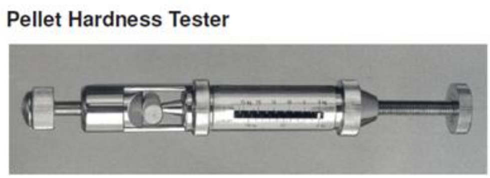


Figure 25. Mechanical durability (left) and compression strength (right) test equipment.

The static conditions necessary for determining equilibrium moisture content were provided through the use of a custom-built condensing dryer used as a climatic testing chamber, Figure 26. The device allows for the measurement and regulation of temperature, humidity, air flow and pressure. The conditions chosen for the EMC measurement were a temperature of 22 °C and relative air humidity (RH) of 85%.

Figure 26. The condensing dryer at VTT used as a climatic testing chamber for the determination of equilibrium moisture content (EMC).

The climatic chamber was turned on and allowed to stabilise under the test conditions. A sample of each pellet type (exceeding 300 grams) was placed in an open tray made of aluminium foil. The measurements continued until the mass of all the samples remained constant – this occurred within an approximate twenty-four hour period. Even after three days in the chamber, no further change was measured in the moisture content of the samples.

To assess the outdoor storage properties of the torrefied wood pellets, rain exposure and water immersion tests were conducted on pellet samples. The rain exposure text was performed as follows: a 1 kg sample of pellets was placed on a 450 mm diameter Retsch 3.15 mm sieve. The amount was sufficient to cover the entire bottom of the sieve with one layer of pellets. The sieve was placed over a container. Simulated rainfall was realised through the use of a spray bottle fitted with fine nozzles. In total, 400 g of water was sprayed over each sample during a one-hour period. Runoff water from the pellets drained through the sieve and was collected in the container beneath. The mass of water not absorbed by the pellets could then be determined. The total amount of water corresponds to rainfall of 2.5 mm per hour – a level of rainfall which statistically occurs in Finland once every decade. This level of rain was predefined beforehand by experimentation.

The pellets were also subjected to a water immersion test. A 500 g sample of each pellet type was placed in a filtration bag which was then submerged for a period of 15 minutes in a five-litre container of water. By weighing the quantity of water after the immersion period, the amount of water absorbed by the pellet sample could be identified. The immersion time was fixed by pretesting.

Moisture content was determined according to the standard EN 14774-1 and bulk density according to EN 15103 [23, 24].

The torrefied biomass pellets and reference pellets used in the durability and storage tests are listed in Table 8. The torrefied wood and forest residue pellets are those produced by ECN in the pilot tests. Another torrefied pellet grade produced by the CENER from beech wood was used as one of the reference fuels.

Table 8. Pellet samples used in the durability and storage tests.

Sample identification	Feedstock material	Torrefaction temperature	Details
TOP WC 235C	Whole tree wood chips	235 °C	ECN, PATRIG
TOP WC 245C	Whole tree wood chips	245 °C	ECN, PATRIG
TOP WC 255C	Whole tree wood chips	255 °C	ECN, PATRIG
TOP FR 240C	Forest residue chips	240 °C	ECN, PATRIG
TOP FR 250C B3	Forest residue chips	250 °C	ECN, PATRIG, 3% binder
TOP (BEECH) CENER	Beech wood	270 °C	CENER, pilot
WOODPELL.	Pine wood	-	Vapo Oy, Finland
BARKPELL.	Pine bark	-	Sweden
STRAWPELL.	Wheat straw	-	Denmark

6.2 Results and discussion

6.2.1 Bulk and energy density, durability

Table 9 summarises the main thermodynamical and mechanical properties of the torrefied pellets and the chosen reference fuels. Two of the pellet grades, the good quality torrefied pellets produced by CENER from beech wood and the bark pellets, exhibit bulk density of over 700 kg/m^3 and good durability. The mechanical durability of the torrefied pellets was on average lower than those of the reference fuels and below the limit value 97.5% of the EN standard (EN 14961-2:2012).

Table 9. Bulk and energy densities, mechanical durability.

Sample ID	Moisture content (wt%)	LHV_{ar} (MJ/kg)	Bulk density (kg/m^3)	Bulk energy density (GJ/m^3)	Durability (%)	Compression strength (kg)
TOP WC 235C	1.4	19.20	556.6	10.69	80	18.5
TOP WC 245C	2.1	20.02	633.1	12.67	92	20.8
TOP WC 255C	1.6	20.27	633.8	12.85	88	20.8
TOP FR 240C	2.8	19.67	681.3	13.40	89	17.5
TOP FR 250C B3	1.0	20.19	643.2	12.99	87	9.5
TOP (BEECH) CENER	3.6	19.55	702.3	13.73	97	21.0
WOODPELL.	6.9	17.68	678.5	12.00	98	20.5
BARKPELL.	9.0	17.78	708.8	12.60	97	20.0
STRAWPELL.	7.5	14.99	559.0	8.38	98	19.0

Durability tests were also performed for the torrefied pellets after the equilibrium moisture content test in the climate chamber. The results are shown in Figure 27. Mechanical durability decreased by units of approximately 10% compared to the initial values. The compression strength test did not display any deterioration due to the increased moisture content of the pellets. The tenacity of the pellets may have increased with the moisture content.

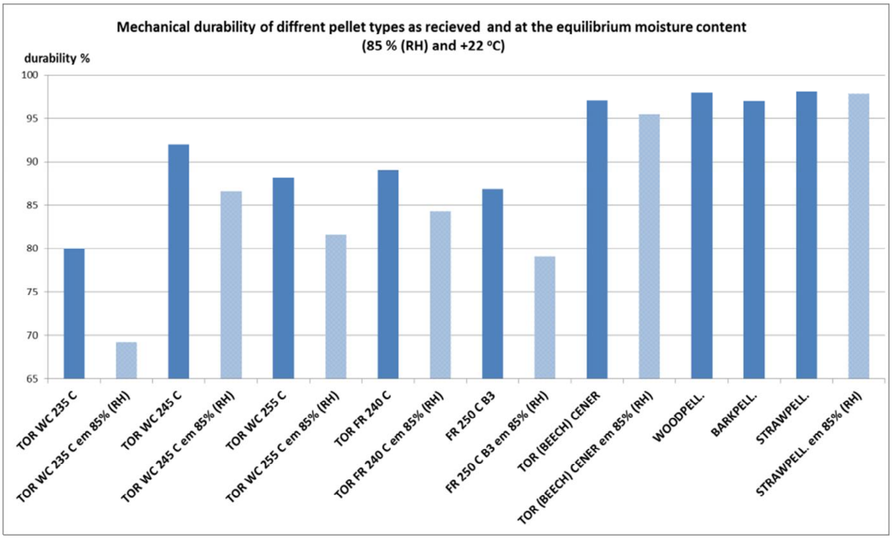


Figure 27. Mechanical durability of pellets before and after the climate chamber tests.

6.2.2 Climate tests

The equilibrium moisture content of the torrefied pellets and some reference pellets was determined in the climate chamber and the conditions chosen for the EMC measurement were a temperature of 22 °C and relative air humidity (RH) of 85%. The results, presented in Figure 28, show that the torrefaction process has a positive effect on humidity uptake from the air. The torrefied pellets can be considered more hydrophobic than the reference biomass pellets. A higher torrefaction temperature also has a favourable influence on hydrophobicity.

The water absorption of the fuel pellets during the rain exposure tests and the immersion tests is depicted in Figure 29. In general, torrefaction at reasonable temperatures seems to enhance the hydrophobicity of the fuel pellets. The torrefaction temperature of 235 °C is clearly too low in this respect. The good quality torrefied beech pellets, with a shiny and hard surface, performed best in these tests. Wood and straw pellets are known to disintegrate quite rapidly when exposed to water. This can be seen in the pictures in Figure 30, and can be interpreted from Figure 29.

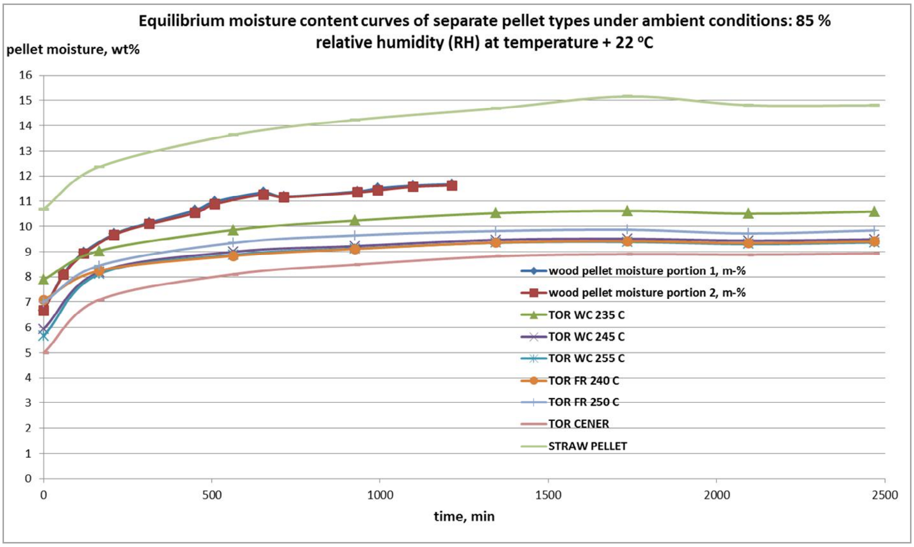


Figure 28. Equilibrium moisture content of torrefied and reference pellets.

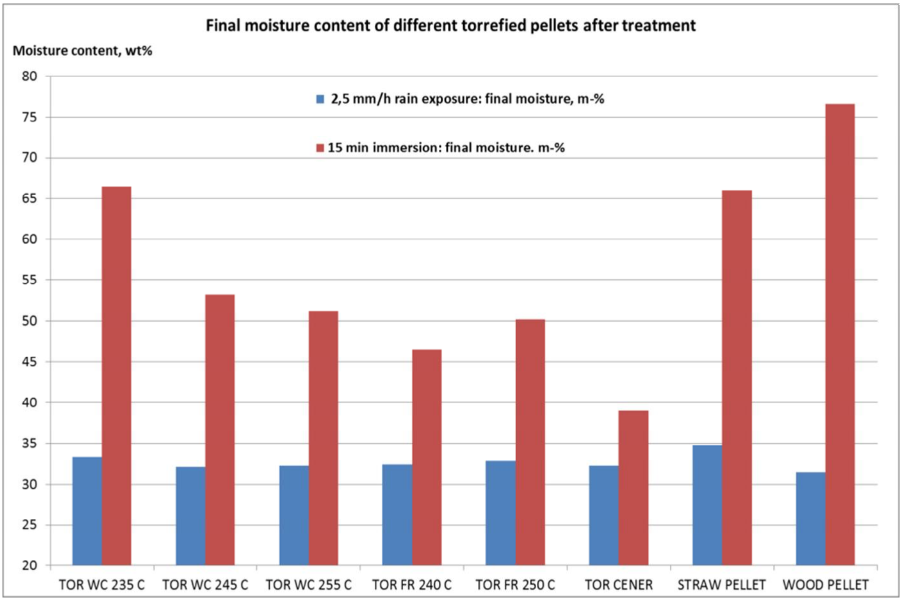


Figure 29. Rain exposure and immersion tests of torrefied and reference pellets.

Figure 30. Wood pellets and torrefied wood pellets before and after the rain exposure tests.

6.3 Conclusions

The increase in heating value and mechanical properties like bulk density and durability is, according to the results obtained in this research work, somewhat more modest than expected based on the public information available. Torrefaction temperatures of between 250 and 270 ^{o}C increases the lower heating value (LHV_{db}) of wood pellets compared to those produced from torrefied wood from about 19 MJ/kg to 21 MJ/kg. A slight increase in bulk density from a level of 650–675 kg/m^3 to 630–700 kg/m^3 may also be accomplished. The increase in energy density of wood pellets from 11–12 GJ/m^3 to 13–14 GJ/m^3 for torrefied wood pellets is mainly accounted for by a lower moisture content of the torrefied pellets.

The mechanical durability of the torrefied pellets was not at the level required by the EN standard, except for that produced at a higher torrefaction temperature from beech wood. The durability decreases by about 10% when the torrefied pellets are exposed to humid conditions and when they reach their equilibrium moisture content. The torrefaction temperature and the properties of the feedstock both influence the pelletability of the torrefied material, but the exact cause and effect is unclear. Experience and the correct pellet dye configuration are, however, required to obtain optimum pellet quality.

The equilibrium moisture content and the rain exposure tests showed that the torrefied pellets are clearly more hydrophobic than wood and straw pellets and do not disintegrate completely on exposure to water. The immersion tests and the rain exposure tests indicated that water absorption is lower for pellets produced in higher torrefaction temperatures which have a denser structure (high bulk density).

Large-scale storage tests are required to have a clear view of the torrefied biomass pellets to withstand outdoor storage in piles, as is the case in coal storage. The partial hydrophobicity of the torrefied pellets and their ability to resist disintegration when wet may result in a reasonably good water tolerating upper layer on stock piles, which protects the bulk of the material from being damaged.

7. Safety-technical properties of torrefied wood

7.1 Introduction

Information on the assessment of risk and prescription of safety measures is largely concerned with spontaneous ignition risks and dust explosions. The knowledge of safety-technical basic characteristics of biomass fuels is of essential significance when designing handling and feeding equipment, planning safety systems and instructions and evaluating fire and explosion hazards. This information is available regarding a variety of commercial fuels [25]. However, hardly any information is available on the ignition and explosion properties of torrefied biomass fuels. Therefore, a limited study on dust explosion and self-ignition characteristics was carried out within the current research programme at the Laboratorio Oficial J.M. Madariaga (LOM) in Spain [26].

7.2 Tests and material

The material used in the characterisation of the safety-technical properties was the torrefied pellets produced from whole tree wood chips at a temperature of 245 ^{o}C (TOP WC 245) in ECN's PATRIG pilot rig. The samples provided for tests were a pellet sample for the self-ignition tests and a dust sample milled from the same pellets for the dust explosion and flammability tests.

7.2.1 Dust explosion test

Dust explosion hazards in atmospheric pressure bins and handling equipment are usually provided for by arranging the discharge of explosion pressure through explosion discs or relief vents and by using explosion suppression systems. The design phase of these safety measures requires input data on the safety-technical properties of new fuels and fuel mixtures created in experimental activities.

A dust explosion can be characterised as combustion of a dust cloud that results in a rapid build-up of pressure or in uncontrolled expansion effects. The generation of a dust explosion requires the simultaneous occurrence of three particular conditions: combustible dust, dispersive air (oxygen) and an ignition source. The explosion severity is usually expressed in terms of:

- maximum explosion over pressure Pmax
- maximum rate of pressure rise (dP/dt)max or Kmax.

These indices are the main ones influencing the assessment and design of different kinds of explosion relief venting and suppression. Limiting oxygen content (LOC) in inertial cases indicates at which ambient oxygen content an explosion is prevented. The lower explosion limit (LEL) describes the minimum concentration of the dust in a dust cloud which may generate an explosion. These explosion characteristics are determined in a 20-litre sphere, Figure 31. The tests performed as part of this project at LOM in Spain are listed in Table 10.

Figure 31. 20-litre sphere used for dust explosion measurements.

Table 10. Explosibility tests.

Parameter	Abbrev.	Applied standard	Test device	Uncertainty
Maximum explosion over pressure	Pmax	EN 14034-1	20-litre sphere	± 10%
Maximum rate of pressure rise	Kmax	EN 14034-2	20-litre sphere	± 10%
Limiting Oxygen Concentration	LOC	EN 14034-4	20-litre sphere	± 1%
Lower Explosion Limit	LEL	EN 14034-3	20-litre sphere	0.1 g/m^3

7.2.2 Self-ignition and flammability tests

Numerous bulk fuels (coal, biomass, wastes...) continuously produce heat due to oxidation processes. Low-temperature reactions with atmospheric oxygen lead to self-heating. With a sufficient material volume and low heat conductivity, heat build-up and spontaneous ignition may occur. Spontaneous heating and ignition phenomena are especially hazardous in storage bins and process equipment, as smouldering material nests are potential ignition sources of more extensive fire and dust explosions. Four primary factors contribute to spontaneous heating:

- oxidation tendency of the material
- ambient temperature
- amount and characteristics of the material
- shape of the storage vessel.

The experimental basis for describing the self-ignition behaviour of a given solid is the determination of the self-ignition temperatures, T_{SI}, of differently-sized bulk volumes of the material by isothermal hot storage experiments in commercially available ovens, Figure 32. The results thus measured reflect the dependence of self-ignition temperatures on material volume.

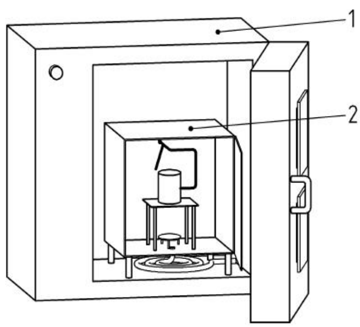


Figure 32. Set-up for determination of self-ignition temperatures. 1. heating oven, 2. inner chamber (volume ≈ 50 l).

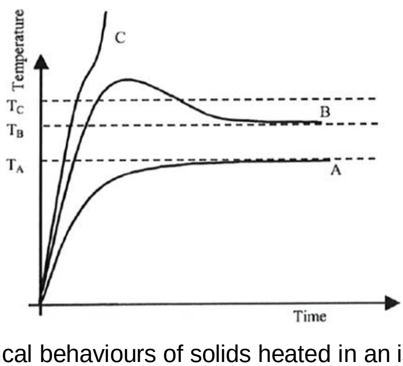


Figure 33. Typical behaviours of solids heated in an isothermal oven.

The sample is introduced to an oven at a set temperature and the evolution of the temperature of the sample is observed over time. There are three types of behaviour in the tests, Figure 33. The supercritical behaviour exhibited by curve C shows that the production of heat reaches a point that exceeds the heat losses, resulting in non-stationary conditions, so that the temperature of the sample increases rapidly above Tc. This case corresponds to spontaneous combustion, since the material reacts strongly and the temperature in the basket rises rapidly, leaving the test product ashes after combustion. The self-ignition temperature is defined as the highest temperature at which a given volume of dust will not ignite.

The ignition temperature of the product is determined for different sample volumes, typically between 50 cm^3 and 1500 cm^3. Once the self-temperature for different sample volumes is obtained, log (V/A) versus temperature ($1/T_{SI}$ in K^{-1}) can be represented in an Arrhenius-type diagram. The regression curve of all test results shows the transition between the stationary and non-stationary behaviour of the samples.

In every test, the auto-ignition temperature and the time taken from reaching the temperature of the oven until ignition occurs (induction time) are recorded. With the help of the above-mentioned diagrams, the size of storage that will lead to spontaneous combustion and also the time needed to produce ignition can be estimated.

The flammability and spontaneous ignition tests performed at LOM are listed in Table 11.

Table 11. Flammability and spontaneous ignition tests.

Parameter	Abbrev.	Applied standard	Test device	Uncertainty
Minimum Ignition Temperature on a layer	MIT-l	EN 50281-2-1:1999	Flat oven (plate)	5 K
Minimum Ignition Temperature in a cloud	MIT-c	EN 50281-2-1:1999	Vertical oven	5 K
Minimum Ignition Energy	MIE	EN 13821:2003	MIKE3	1 mJ
Self-ignition Temperature	T_{SI}	EN 15188:2008	Isothermal oven	5 K

7.3 Results

7.3.1 Explosion severity

The dust explosion tests in the 20-litre sphere were conducted over a dust concentration range (explosive range) of 125–2250 g/m^3. The optimum dust concentration was found to be 1250 g/m^3. The Limiting Oxygen Concentration of a dust cloud (LOC) is defined as the maximum oxygen concentration in a mixture of combustible dust and air and an inert gas, in which an explosion will not occur.

Table 12 shows the results obtained in these tests and as a comparison corresponding values measured for other fuel dusts [25].

Table 12. Explosion parameters of different dusts.

	Explosion pressure Pmax (bar g)	Rate of pressure rise Kmax (m*bar/s)	Limiting Oxygen Concentration LOC (%)
Torrefied wood dust	9.0	150	11
Wood dust	9.1-10.0	57-100	10-12
Peat dust	9.1-11.9	120-157	13.5
Lignite dust	9.4-11.0	90-176	13-15
Coal dust	8.9-10.0	37-86	14

The explosion class is defined as a function of the Kmax values, as indicated in Table 13. The torrefied wood dust is a class St1 dust, as with most fuel dusts.

Table 13. Explosion class.

Explosion class	Kmax value (m*bar/s)	
St0	0	non-explosive
St1	≤ 200	weak, normal
St2	201–300	strong
St3	> 300	violent

7.3.2 Thermal stability

The flammability parameters of torrefied wood dust and other fuel dusts are presented in Table 14. The Minimum Ignition Energy (MIE) of a dust cloud measured for torrefied wood dust was 160 mJ, which is of the same magnitude as that of other biomass dusts. Coal dust usually has an MIE to the order of > 1000 mJ. Generally it can be concluded that the torrefied wood dust is more sensitive to ignition due to elevated temperatures or e.g. electrical sparks than coal dust.

Table 14. Flammability temperatures.

	Minimum Ignition Temperature in a dust cloud (°C)	Minimum Ignition Temperature on a layer (°C)
Torrefied wood dust	460	330
Wood dust	420	340
Peat dust	470–590	305–340
Lignite dust	410–450	230–250
Coal dust	590–760	270–450

The self-ignition tests were carried out with torrefied wood pellets. Table 15 presents the self-ignition temperatures and induction times obtained with different cylindrical cell sizes.

Table 15. Results of tests in the isothermal oven.

Cell size (cm^3)	Lower temp. resulting in ignition (°C)	Higher temp. without ignition (°C)	Ignition temperature TSI (°C)	Induction time (min)
50	190	185	187.5	54
150	170	165	167.5	71
350	160	155	157.5	130
1500	145	140	142.5	317

Figures 34 and 35 show the extrapolated results for the torrefied wood pellet sample. In both figures, the ordinate shows the logarithm of the characteristic dimension (volume/area). In the case of a cubic enclosure of side h (or cylindrical with height h equal to diameter) V/A = h/6.

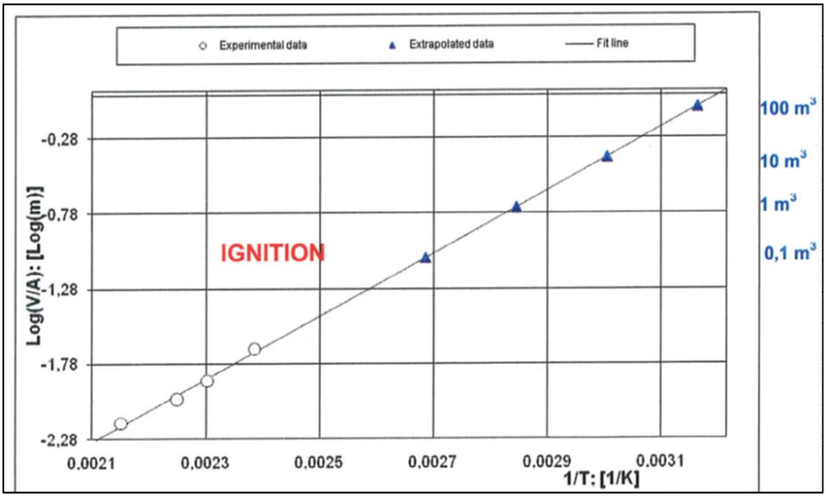


Figure 34. Extrapolation of results: size versus temperature.

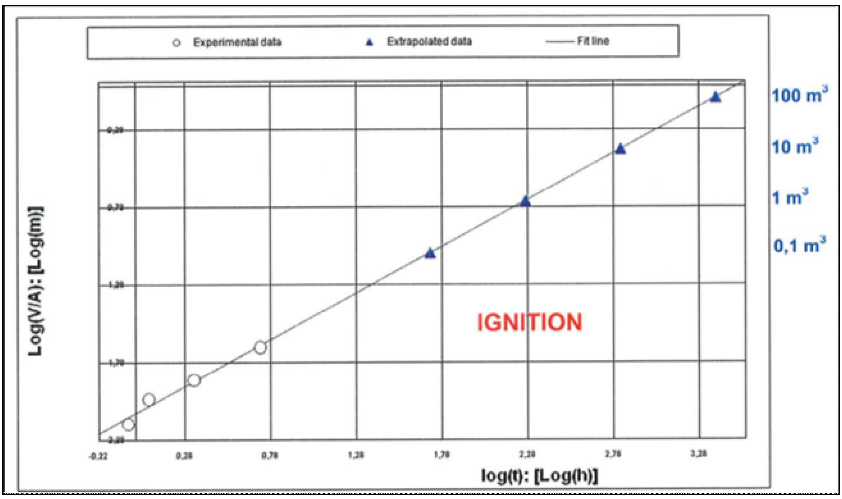


Figure 35. Extrapolation of results: size versus time.

Table 16 summarises the interdependence between the size of storage bin (cubic), storage temperature and induction time. Given the experimental features of the test method and this interpretation of results through a process of extrapolation, these values should be viewed with caution. Therefore, the lines outlining the region of ignition from the region of non-ignition in Figures 34 and 35 should be regarded as uncertainty regions (bands instead of lines), so that the closer the characteristic point is to the line, the greater the uncertainty about the outcome of ignition or non-ignition.

Table 16. The influence of (cubic) storage size, temperature and time on the self-ignition behaviour of torrefied wood pellets.

Storage size (m^3)	Temperature (°C)	Induction time
100	41.0	3.4 months
10	57.6	28 days
1	75.9	7.8 days
0.1	96.4	2.2 days

7.4 IMO test for the transportation of dangerous goods

IMO is the United Nations' specialist agency responsible for the safety and security of shipping and the prevention of marine pollution by ships. IMO 4.1 and IMO 4.2 tests were carried out by TNO on crushed torrefied wood pellets according to the methods and criteria set by the United Nations Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, fifth revised edition [27]. The torrefied wood sample chosen for the tests was the same as that used in the dust explosion tests: pellets produced from whole tree wood chips at a temperature of 245 °C (TOP WC 245). Crushed pellet samples were used because it may simulate a certain degree of disintegration occurring in handling and shipping operations.

7.4.1 Test procedures

The IMO 4.1 flammability test is basically designed to test powders and granules. Powder is put in a 250 mm-long mould with a triangular cross section and is somewhat compressed. Then the mould is turned and the content is placed on a flat floor (the mould is removed). The result is a 250 mm-long strip of material as shown in the Figure 36. One side of the strip is ignited and the time needed for the flame to burn along 200 mm of the strip is measured. The time is a measure for the ability of the material to propagate combustion. If the time is longer than 2 minutes, then the material should not be classified as a flammable substance.

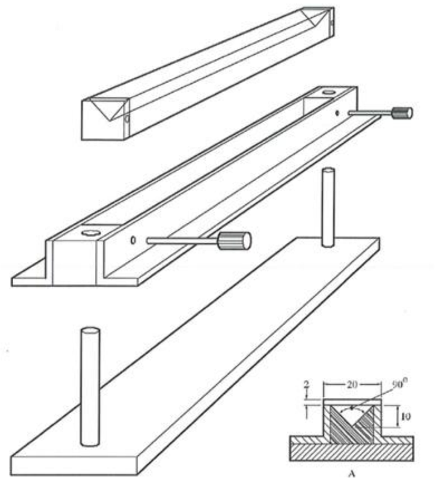


Figure 36. Mould and accessories for the burning rate test.

The IMO 4.2 self-heating test is carried out in a similar oven set up as described in section 8.2.2. The test is conducted using a cubic sample container with 100-mm sides, at an oven temperature of 140 °C. The oven temperature is raised to the required temperature and kept there for 24 hours. The temperatures of the sample and the oven are monitored continuously. A sample temperature rise of more than 60 °C above the oven temperature or spontaneous ignition is considered self-heating.

7.4.2 Results and conclusions

Based on the test results [28], it is concluded that the investigated sample of crushed torrefied wood pellets is not flammable and has no self-heating properties in the sense of the criteria laid down in the United Nations Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, fifth revised edition. Consequently, the material does not need to be classified as a flammable solid or as a self-heating substance.

7.5 Conclusions

As with most of the dusts generated during biomass handling, pre-treatment and processing steps, dust and dust layers of torrefied biomass are susceptible to dust explosions and self-ignition. The safety-technical characteristics of the torrefied dust do not differ significantly from those of normal biomass dust, but are clearly more reactive than coal dust. Torrefied wood pellets are drier and more brittle than conventional wood pellets. Severe dusting during the unloading and conveying of torrefied pellets has been observed. Due to a very fine particle size and almost zero moisture content, the torrefied dust may ignite more easily and thus create a larger dust explosion risk than conventional biomass dusts and coal dust. The elimination of dust formation and ignition sources is therefore critical in the whole utilisation chain. The self-heating and spontaneous ignition behaviour of the torrefied wood pellets is more difficult to predict, partly because of the long time span these reactions require, but these hazards cannot be neglected in the large-scale storage of the fuel.

8. European market perspective

8.1 Market potential

The market for torrefied fuels is primary driven by utilities that want to co-fire large amounts of biomass to reduce their dependence on fossil coal. National feed-in tariffs are boosting the co-firing of biomass to replace fossil fuels to higher shares, which are technically possible to reach with commercial white wood pellets. A certain amount of potential is also foreseen in the residential and industrial heating sector. If the production is to match the presumed market potential, large-scale production with a similar capacity to the recent wood pellet plants (100–500,000 t/a) is expected. Pöyry [29] has estimated that a 5% (energy base) replacement of coal with wood pellets in co-firing would require a tripling of the current European wood pellet production, Figure 37. Considering the fact that the replacement with torrefied wood pellets could be as high as 50%, this makes the European market hugely significant.

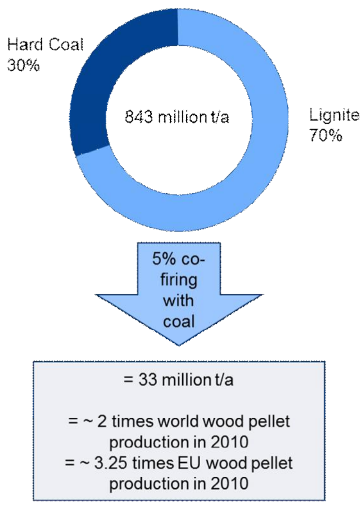


Figure 37. Wood pellet co-firing potential in more than 100 existing pulverised coal-fired plants in Europe 2010 [29].

According to Pöyry, Western Europe will be the largest wood pellet consumer in the future. The consumption is estimated to grow from about 12 million tonnes in 2010 to 25 million tonnes in 2020 [29]. Although the largest pellet production capacities are forecasted to remain in Europe, a region with strong competition for raw material, the growing demand will increasingly be satisfied by imports from other regions. Imports from North America dominate and the transatlantic trade of pellets exceeded 3 million tonnes in 2012 [30]. The largest trade streams within Europe are going from Eastern Europe and Russia to Western Europe. The global pellet trade streams are depicted in Figure 38. There is good reason to believe that the future trade flows of torrefied biomass pellets will follow the same routes as the current wood pellets trade streams.

Concern regarding the sustainability of solid biomass and new EU directives may change future market perspectives. The production of second generation biofuels for transport is also a potential consumer area that has not been discussed here due to highly diverse business scenarios.

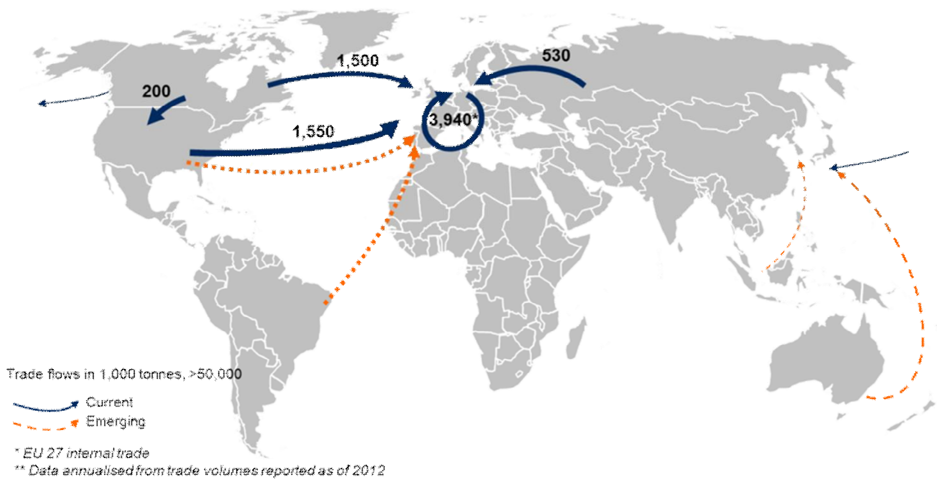


Figure 38. Global wood pellet trade flows in 2012 [30].

8.2 Woody biomass availability

European wood resources offer a raw material base for a variety of industries such as sawn wood, wood panels, pulp and paper, and bioenergy. From the geographical point of view, forests are unevenly distributed in the EU, with Germany, France, Sweden and Finland having the largest forest resources. There are also variations in the wood processing structure with the pulp industry playing an important role in the Nordic countries, whereas in Central Europe the wood products industry is the largest wood processing sector.

In general, the sawmill industry is the largest wood processor in the EU with a 45% share of the total industrial wood intake. The pulp industry represents around 35% and the panel industry around 20% of the total industrial wood intake in the EU. However, this accounting includes double counting, as a large share of sawmilling residues is used in the pulp and panel industry but also in the energy industry. The utilisation rate of forest industry residues and by-products is relatively high in the EU, indicating that there are no large quantities of surplus residues available for energy or other purposes. Wood supply in Central Europe remains more or less stable. Regions with significant growth potential are mainly the southern United States, South America, Canada, Russia and Africa [30], Figure 39.

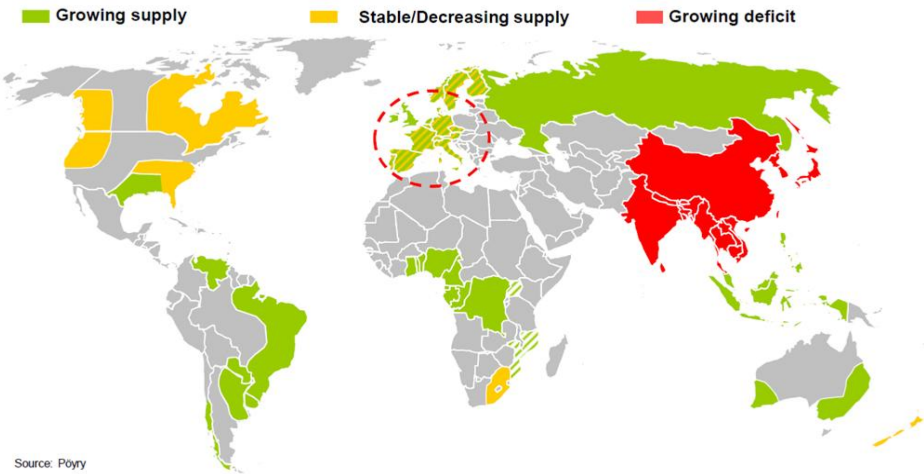


Figure 39. Global woody biomass availability [30].

The growth of the European forests exceeds the current harvest, indicating the potential to increase roundwood harvesting in the EU. The EUwood publication [31] presents an analysis of forest biomass supply potential in the EU. According to the analysis, the theoretical forest biomass supply potential in the EU amounts to around 1.3 billion m³, of which 52% consists of stemwood, 26% of harvest residues and 22% of stumps and other residues.

Utilisation of the theoretical forest biomass supply potential is, however, restricted by various environmental, social, technical and economic constraints. Based on the EUwood analysis, the realistic forest biomass supply potential in the EU amounts to about 750 million m³, of which around 630 million m³ consist of stemwood and the rest, 120 million m³, mainly of harvest residues.

According to FAOSTAT, the total roundwood harvest in EU amounted to around 480 million m³, indicating an additional stemwood harvest potential of around 150 million m³. There are no consistent statistics available on the amount of collected harvest residues in the EU, but it can be estimated that the additional harvest residues collection potential is around 100 million m³, as the harvest residue collection amounts are still relatively small in Europe. This indicates an additional forest biomass supply potential of around 250 million m³ in the EU.

Assuming that only pulpwood and harvest residues are suitable assortments for torrefied pellets rather than logs, the total amount of forest biomass suitable for torrefied pellets amounts to around 175 million m³. This is based on an assumption that pulpwood represents 50% of the total stemwood potential, resulting in 75 million m³ of pulpwood and 100 million m³ of harvest residues. If all the available volume were to be used for torrefied pellets, it would yield around 55 million tonnes of pellets. This equals to roughly 10–15% (energy base) of the total consumption of hard coal in the EU27. The assumption of using all the available wood suitable for torrefied pellets is, however, highly theoretical due to fast growing markets needs in other energy sectors, such as the production of transportation fuels and other high value products.

Despite the restrictions related to large-scale mobilisation of the European biomass resources, there are several opportunities for a number or individual new bioenergy projects, such as torrefied pellets, boosted by the non-permanent feed-in tariffs. For a new operator, the capability to pay for the raw material plays a significant role in entering the wood market. At the moment, the cost of pulpwood at mill in Europe is somewhere between 30–55 EUR/m³ sob (solid over bark), as presented in Figure 40, meaning that the torrefied pellet industry needs to have a wood-paying capability equivalent to prevailing wood prices in order to compete with other wood processing sectors.

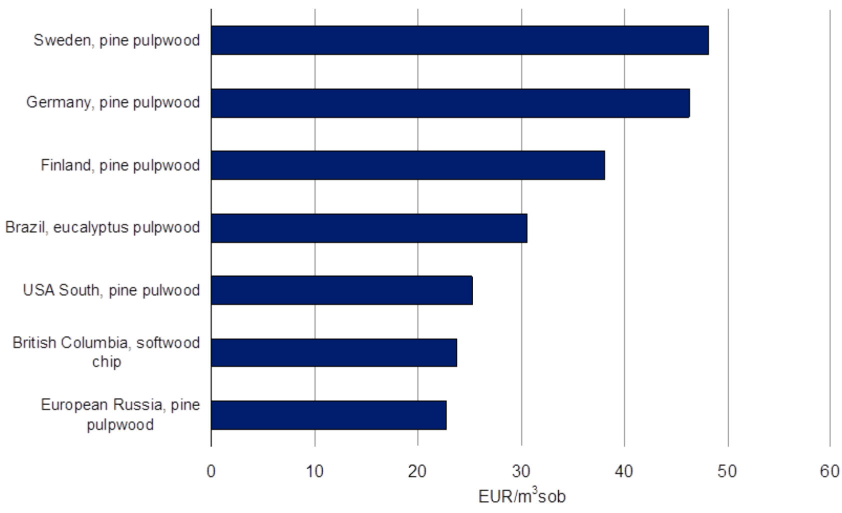


Figure 40. Pulpwood costs in selected regions, 2012 (Pöyry database).

On a global scale, there are vast untapped forest biomass resources supporting high-level development of a variety of wood processing industry sectors, such as torrefied pellets. When focusing on individual business cases, the primary focus is not necessarily on macro-level wood availability, but on biomass resources that are sustainable, large enough for an individual mill and accessible at a reasonable level of effort and cost. In this case, smaller amounts of biomass can also be of interest, such as forest industry residues that have been tapped from the forests but have remained unutilised at the wood processing site. In general, the utilisation rate of forest industry residues is relatively high, but for example in Russia and Canada there might be opportunities to find surplus volumes of forest industry residues. In Russia there is also the potential to increase the utilisation of low-quality roundwood originating as a by-product from industrial roundwood harvesting.

In the southern United States, the decrease in forest industry production in the past has increased the amount of unmobilised plantation wood in the region. Currently the amount of unmobilised forest biomass in the south-eastern United States is somewhere around 100 million m^3. Commercially focused forestry practices supporting wood mobilisation makes the region an attractive basis for new biomass-based investments. In Brazil, plantation-based forestry may offer potential for bioenergy-related operations.

9. Summary and conclusions

There is growing interest both in Finland and internationally to substitute fossil coal in power and heat production, given the potential for the significant environmental benefits in terms of net CO_2 emission reductions and fulfilling the European and national 2020 targets for renewable energy. One current option is to use torrefied biomass as a fuel, especially as pellets for co-firing in pulverised coal-fired power plants. This publication summarises the results of experimental work on torrefaction carried out with Finnish wood fuels.

Five wood fuels were chosen for preliminary laboratory-scale testing at ECN in the Netherlands. Based on the results, two typical wood fuels, wood chips and crushed forest residue chips, were chosen for pilot-scale tests in the ECN PATRIG torrefaction test rig. Temperature ranges from 235 to 260 ^{o}C were tested. The PATRIG production runs confirmed that with the torrefaction temperatures mentioned, good quality torrefied materials were produced except at 235 °C. Here the torrefaction temperature was too low. Furthermore, it was confirmed on a semi-industrial scale that good pellets can be produced from these materials except for the 260 °C torrefied forest residue chips. Overall, it can be concluded that whole tree chips and forest residue chips can be torrefied in quite a broad temperature range, but pelletising the torrefied wood fuels produced at high torrefaction temperatures is not a straightforward procedure and may need some adjustments and binders to be successful.

CFD was applied to simulate the co-firing of torrefied wood biomass with coal in a pulverised coal-fired furnace. The goal of the work was to investigate the feasibility of torrefied fuels to replace part of the coal from the combustion and furnace process point of view. From the combustion point of view it seems feasible to replace coal with torrefied wood biomass in the unit investigated with shares of up to 50% by weight. NO_x emissions are reduced when the share of biomass-based fuel is increased. A reduction of up to 20% might be possible in torrefied biomass co-firing. Evaporator wall fouling/corrosion problems are not expected to increase.

Common expectations of torrefied wood pellets regarding storage and handling properties have been high, but little information relating to practical experience is available. Basic small-scale experiments were carried out to compare torrefied wood pellet properties with conventional wood and straw pellets. The mechanical durability of the torrefied pellets were not at the level required by the EN standard, except for the one produced at a higher torrefaction temperature from beech wood. Durability decreases by about 10% when the torrefied pellets are exposed to humid conditions and reach their equilibrium moisture content. The equilibrium moisture content and the rain exposure tests showed that the torrefied pellets are clearly more hydrophobic than wood and straw pellets and do not disintegrate completely on exposure to water. Water absorption is lower for pellets produced at higher torrefaction temperatures having a denser structure. Large-scale storage tests are required to provide a clear view of the ability of torrefied biomass pellets to withstand outdoor storage in piles, as is the case in coal storage.

The knowledge of basic safety-technical characteristics of biomass fuels is of essential significance when designing handling and feeding equipment, planning safety systems and instructions and evaluating fire and explosion hazards. However, hardly any information is available on the ignition and explosion properties of torrefied biomass fuels. Therefore, a limited study on dust explosion and self-ignition characteristics was carried out. The safety-technical characteristics of the torrefied dust do not differ significantly from those of normal biomass dust, but are clearly more reactive than coal dust. Torrefied wood pellets are drier and more brittle than conventional wood pellets. Severe dusting during the unloading and conveying of torrefied pellets has been observed. Due to a very fine particle size and almost zero moisture content, torrefied dust may ignite more easily and thus create a larger dust explosion risk than conventional biomass dusts and coal dust. The elimination of dust formation and ignition sources is therefore critical in the whole utilisation chain.

The commercial development of torrefaction is currently in its early phase. Several technology companies and their industrial partners are moving towards commercial market introduction. The current general view is that most of the demonstration plants have technical problems which have delayed their commercial operation. The market is expected to move forward but the available public information is very limited, especially concerning the technologies used and volumes produced.

It is estimated that it would be possible to replace about half of the solid fuel with torrefied pellets in pulverised coal-fired combined heat and power plants without major new investments. A prerequisite for this is that the torrefaction process is able to convert the biomass to a satisfactorily brittle solid fuel to be milled together with coal, in order to produce a fuel mix which fulfils the requirements of the PC boiler. Considering the fact that replacement with torrefied wood pellets could be as high as 50% makes the European market hugely significant.

The utilisation rate of forest industry residues and by-products is relatively high in the EU, indicating that there are no large quantities of surplus residues available for energy or other purposes. Wood supply in Central Europe remains more or less stable. Despite the restrictions related to large-scale activation of the European biomass resources, there are several opportunities for a number of individual new bioenergy projects, such as torrefied pellets. However, the capability to pay for the raw material plays a significant role in entering the wood market.

Further development of torrefaction technologies and supporting activities on the market introduction of torrefaction-based bioenergy carriers are the focus areas of an ongoing (2012–2015) EU project entitled Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction “SECTOR” [32]. The project is coordinated by the German Biomass Research Centre (DBFZ). VTT is one of the 22 participants involved in the project.

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Series title and number
VTT Technology 122

Title	**Wood torrefaction – pilot tests and utilisation prospects**
Author(s)	Carl Wilén, Perttu Jukola, Timo Järvinen, Kai Sipilä, Fred Verhoeff & Jaap Kiel
Abstract	The research project "Torrefaction of woody biomasses as energy carriers for the European markets" was carried out within the Tekes BioRefine programme in 2010–2012 and was coordinated by VTT. The main objective of the project was to create a discussion platform and collate basic information for the Finnish industrial stakeholders involved in developing torrefaction technology or planning to include torrefied biomass in their fuel supply for energy production. Given the availability of torrefaction pilot facilities in Europe, it was decided at an early phase of the national torrefaction research project not to build and operate separate pilot equipment and thus save time and money. Experimental research was conducted in cooperation with ECN, the Netherlands. Finnish wood chips and crushed forest residue were tested at different torrefaction temperatures in the PATRIG torrefaction test rig with great success, and large quantities of torrefied wood chips and pellets were produced. CFD simulation work was carried out at VTT to investigate the feasibility of torrefied fuels to replace some of the coal. From the combustion point of view, it seems feasible to replace coal with torrefied wood biomass with shares of up to 50% by weight. Basic small-scale experiments were carried out to compare torrefied wood pellets with conventional wood and straw pellets with regard to their handling and storage properties. The experiments showed that the torrefied pellets are clearly more hydrophobic than wood and straw pellets and do not disintegrate completely on exposure to water. A study on dust explosion and self-ignition characteristics indicated that the torrefied dust does not differ significantly from normal biomass dust, but is clearly more reactive than coal dust. Commercial development of torrefaction is currently in its early phase. The current general view is that most of the demonstration plants have technical problems which have delayed their commercial operation. The market is expected to move forward but the available public information is very limited, especially with regard to the technologies used and volumes produced. Woody feedstocks will be the main raw material source. The utilisation rate of forest industry residues and by-products is relatively high in the EU and the wood supply in Central Europe remains more or less stable, hence the price of the raw material is at a fairly high level. The utilities' capability to pay for the product depends mainly on the national feed-in tariffs of green electricity. The energy price for the user is at least twice as high as that of coal.
ISBN, ISSN	ISBN 978-951-38-8046-0 (Soft back ed.) ISBN 978-951-38-8047-7 (URL: http://www.vtt.fi/publications/index.jsp) ISSN-L 2242-1211 ISSN 2242-1211 (Print) ISSN 2242-122X (Online)
Date	September 2013
Language	English, Finnish abstract
Pages	73 p.
Name of the project	Torrefaction of woody biomasses as energy carriers for the European markets
Keywords	Torrefaction, pellets, biomass, co-firing, pilot plant, storage, safety issues, simulation
Publisher	VTT Technical Research Centre of Finland P.O. Box 1000, FI-02044 VTT, Finland, Tel. +358 20 722 111

Julkaisun sarja ja numero

VTT Technology 122

Nimeke	**Puun torrefiointi – pilot-kokeet ja käytön edellytykset**
Tekijä(t)	Carl Wilén, Perttu Jukola, Timo Järvinen, Kai Sipilä, Fred Verhoeff & Jaap Kiel
Tiivistelmä	Tutkimusprojekti ”Torrefaction – Uudet verkottuneet biojalostamot Euroopan pelto- ja metsäbiomassan energiakantajaksi” toteutettiin Tekesin BioRefine-ohjelmassa VTT:ssä vuosina 2010−2012. Tavoitteena oli luoda keskustelufoorumi ja koota yhteen perustietoa alan suomalaisille toimijoille, jotka ovat kiinnostuneita torrefiointiteknologian kehittämisestä tai suunnittelevat biohiilen ottamista polttoainevalikoimaansa. Projektin suunnitteluvaiheessa päätettiin hyödyntää Euroopassa tutkimuslaitoksilla olevia pilot-kokoluokan koelaitteistoja oman laitteiston rakentamisen sijasta ajan voittamiseksi ja kustannusten säästämiseksi. Biohiilen tuotannon kokeellinen tutkimus tehtiin yhteistyössä ECN:n kanssa Hollannissa. Suomalaisilla puuhakkeilla tehtiin onnistuneet koeajot eri torrefiointilämpötiloissa PATRIG-koelaitteistolla ja tuotettiin merkittävät määrät hiillettyä puuhaketta ja siitä pellettejä jatkotutkimuksia varten. VTT:ssä tehdyllä CFD-kattilasimuloinnilla selvitettiin hiilen korvaamista torrefioidulla puuhakkeella. Tuloksena todettiin, että polton kannalta kivihiiltä voidaan korvata pölypolttokattilassa biohiilellä ainakin 50 painoprosenttiin asti. Torrefioiduilla pelleteillä tehtiin pienimuotoisia käsittely- ja varastointikokeita ja verrattiin torrefioitujen pellettien ominaisuuksia kaupallisten puu- ja olkipellettien vastaaviin ominaisuuksiin. Kokeet osoittivat, että biohiilipelletit ovat hydrofobisempia kuin puu- ja olkipelletit eivätkä hajoa täysin joutuessaan veden kanssa kosketukseen. Pölyräjähdys- ja itsesyttymistutkimuksissa todettiin, että biohiilen turvallisuustekniset ominaisuudet eivät merkittävästi eroa muiden biomassapölyjen ominaisuuksista, mutta biohiilipöly on selvästi reaktiivisempaa kuin hiilipöly. Torrefiointiteknologian kaupallistaminen on edelleen Euroopassa kehitysvaiheessa. Usean demonstraatiolaitoksen tekniset ongelmat ovat viivästyttäneet laitosten kaupalliseen tuotantoon saattamista. Tuotannon odotetaan käynnistyvän, mutta käytettävästä teknologiasta ja tuotantomääristä on vain rajallista julkista tietoa. Tulevan käytön ensisijaiset raaka-aineet ovat puuperäiset polttoaineet. Koska metsäteollisuuden sivuvirtojen käyttöasteet EU:ssa ovat jo suhteellisen korkeat ja Keski-Euroopan puun tuotanto on vakiintunut, lisäraaka-aineen hinta on melko korkealla tasolla. Tuotteen maksukyvyn määräävät pääosin eri maissa maksettavan vihreän sähkön syöttötariffit. Torrefioitu puupelletti on käyttäjälle vähintään kaksi kertaa kalliimpi energiahinnaltaan kuin kivihiili.
ISBN, ISSN	ISBN 978-951-38-8046-0 (nid.) ISBN 978-951-38-8047-7 (URL: http://www.vtt.fi/publications/index.jsp) ISSN-L 2242-1211 ISSN 2242-1211 (painettu) ISSN 2242-122X (verkkojulkaisu)
Julkaisuaika	Syyskuu 2013
Kieli	Englanti, suomenkielinen tiivistelmä
Sivumäärä	73 s.
Projektin nimi	Torrefaction – Uudet verkottuneet biojalostamot Euroopan pelto- ja metsäbiomassan energiakantajaksi
Avainsanat	Torrefaction, pellets, biomass, co-firing, pilot plant, storage, safety issues, simulation
Julkaisija	VTT PL 1000, 02044 VTT, puh. 020 722 111

VTT TECHNOLOGY 122 Wood torrefaction – pilot tests and utilisation prospects

Wood torrefaction – pilot tests and utilisation prospects

There is a growing interest in Finland and internationally to substitute fossil coal in power and heat production, given the potential for significant environmental benefits in terms of net CO_2 emission reductions. The torrefied and pelletised biocoal product shows a large resemblance to coal and allows high co-firing percentages without major investments in modified handling and milling systems.

Finnish wood chips and crushed forest residue were tested at different torrefaction temperatures in cooperation with ECN with great success, and large quantities of torrefied wood chips and pellets were produced. CFD simulation work was carried out at VTT to investigate the feasibility of torrefied fuels to replace part of the coal. From the combustion point of view it seems feasible to replace coal by torrefied wood biomass with shares up to 50% by weight. Small-scale experiments were carried out to compare torrefied wood pellets with conventional wood and straw pellets with regard to their handling and storage properties. A study on dust explosion and self-ignition characteristics indicated that the torrefied dust does not differ significantly from the normal biomass dust, but is clearly more reactive than coal dust.

Commercial development of torrefaction is currently in its early phase. The current general view is that most of the demonstration plants have technical problems, which have delayed their commercial operation.

ISBN 978-951-38-8046-0 (Soft back ed.)
ISBN 978-951-38-8047-7 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN-L 2242-1211
ISSN 2242-1211 (Print)
ISSN 2242-122X (Online)